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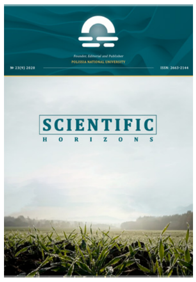

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Differential diagnosis of chronic infertility in high-yield cows

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Abstract. The infertility of cows and heifers has been the most pressing problem in the livestock sector. The genitals and mammary gland have an increased functional load associated with pregnancy, childbirth, and lactation. The purpose of this study was to determine the prevalence of symptoms of chronic irreversible infertility in Ayrshire cows culled as a result of multiple artificial inseminations. The study employed analytical, structural-comparative, and statistical methods, as well as a modified

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differential palpation diagnosis of the clinical state of the reproductive organs in the ovary+oviduct area with lateral localisation was consistently applied in two stages. The findings of the study showed that cows with in vivo diagnosed symptoms of chronic adherent salpingitis and ovosalpingitis (52.17%), i.e., irreversible form of infertility, had significantly higher (+28.05%; P < 0.01) milk production and better lactation compared to those without these pathologies. Furthermore, in the group of cows culled due to numerous ineffective inseminations, related gonadopathies were detected: from 4.35% to 10.87% of ovarian hypotrophy, 4.35% of gonadal sclerosis symptoms and 17.39% of cystic follicular degeneration cases. In 73.91% of females, the presence of sexual cyclicity with unchanged ovarian function in the follicular phase and in 84.78% – in the luteal phase of the cycle was established. The use of differential palpation diagnostics in production conditions allows in vivo predicting the tendency to loss of genetic resources (the ability of cow ovaries to maintain generative and secretory functions) in highly productive cows due to chronic inflammatory gynecological pathologies, which will contribute to the improvement of drug and biotechnological schemes of therapeutic measures for the prevention of infertility in the dairy herd

Keywords: dairy cows; genetic resources; chronic infertility; ovaries; oviducts; chronic inflammatory gynecological processes; salpingitis; adhesions

INTRODUCTION

Reproduction of dairy herds is one of the principal areas of veterinary medicine and reproduction biotechnology in countries with developed agriculture. Considering the long period of rearing a first-calf cow, the retirement of dairy cows due to gynaecological diseases and chronic infertility is a substantial factor in reducing the production costs of each dairy enterprise. The data obtained by D.A. Vallejo-Timaran *et al.* (2021), C.E. Cardoso Consentini *et al.* (2021) show that these losses become much more significant if the culling of a high-yielding cow occurs during the first or second lactation. The number of daughters produced by a high-yielding cow directly and indirectly affects not only the sustainability and profitability of dairy production, but also the overall breeding progress of the breed and the formation of high-yielding dairy herds as the biological basis of the dairy cattle industry (Madureira *et al.*, 2023).

A. Praxitelous *et al.* (2023), Z. Várhidi *et al.* (2024) provide a variety of therapeutic and stimulating schemes for the treatment and prevention of gynecological diseases of dairy cows, but the results of the analysis of production data indicate a lack of effectiveness of the recommended veterinary measures. Based on experimental studies, P. Yama *et al.* (2022) found that the production life of dairy cows of modern dairy breeds is constantly decreasing. According to J.-K. Jeong and I.-H. Kim (2022), chronic cow infertility is common among the livestock of all dairy farms, with prevalence ranging within 16-80%. It is necessary to address the negative impact of chronic infertility of dairy cows, which is often not recorded by veterinarians, namely, a significant reduction in the effect of breeding progress of the breed due to the elimination of the best genotypes of cows. As a result of the absence of offspring in the culled first-breeding heifer, it is impossible to further form a qualitative mechanism for the selection improvement of the gene pool, as evidenced by the publications of Ukrainian researchers (Klimkovetskaya *et al.*, 2024).

Insufficient study of the causes of chronic, especially irreversible infertility in dairy cows may contribute to the use of inadequate gynecological therapeutic and hormonal stimulation regimens that have negative consequences for production. The initial and key stage in the prevention and treatment of gynecological pathologies in female cattle is the differential diagnosis of gynecological diseases, which forms the basis for the development of effective therapeutic and stimulating regimens. According to W. Chaikol *et al.* (2022), the key factors of decreasing the profitability of milk production in industrial complexes are directly or indirectly related to diseases of the reproductive system of cows and heifers. Comprehensive morphological studies on the morphological, functional, or pathological analysis of the reproductive tract in the ovary-oviduct region are only fragmentary in the literature, and as a rule, the studies were performed on slaughtered pathological organs (Kudo *et al.*, 2021). H.M. Kyaw *et al.* (2021) conducted a pathological examination of ovarian follicles and corpus luteum to confirm chronic infertility.

In connection with the above, the study attempted to determine the clinical and morphological manifestations of reproductive organs pathology in the important, but difficult to access in vivo in real time, anatomical structure “ovary + oviduct”. This approach allows accurately identifying the pathological processes that cause the cow infertility. The analysis of literature sources demonstrates the contradictions in the interpretation of symptoms of gynecological pathologies using different methodological schemes, which indicates the need for detailed study of the pathogenesis of the formation of the symptom complex “irreversible chronic infertility” in real production conditions. That is why the purpose of this study was to determine the prevalence of clinical symptoms of irreversible pathomorphological changes in tissues in reproductive tract “ovary + oviduct” among highly productive culled cows.

MATERIALS AND METHODS

The experimental part of the study was conducted in 2022-2023 at a leading breeding farm that was part of the association of dairy enterprises in the agricultural sector of Poltava Oblast of Ukraine. The farm uses intensive milk production technology (550 heads of a dairy herd of Ayrshire cows of domestic breeding) and breeds young animals for breeding. The average annual productivity of the herd was 6,000 kg of milk base fat per standard lactation.

The cattle were kept in a mixed type of housing: in winter – keeping livestock on a leash, in summer – loose livestock keeping in a summer camp. The in-house produced fodder base was stable, and the daily ration was compiled following modern zootechnical standards in terms of ingredients and nutritional value, considering the level of milk production and the physiological state of the animals. According to the variable nature of the housing, full-mixed feed rations were changed using feed produced in-house and purchased by the seasons. The farm used three times a day machine milking with individual accounting of milk yields from each cow using a computer system with the Buryonka breeding programme. All livestock were provided with sanitary and veterinary support by the farm's specialists, with a planned schedule of participation of scientists from research institutions in Poltava and Kharkiv oblasts to improve the skills of the staff. According to the current veterinary guidelines, the farm carried out scheduled measures to prevent cattle diseases and scheduled vaccinations against infectious diseases.

The breeding stock was covered by obstetric and gynecological dispensary, but the problem of increasing the yield of newborn breeding heifers, the demand for which was constantly growing for sale to other farms, needed to be addressed. The premature culling of high-yielding cows due to chronic infertility (with a history of multiple ineffective artificial inseminations) required an innovative methodology to solving the problem. Considering the numerous gynecological disease treatment regimens and hormonal stimulation of sexual cycles used on the farm, which were of low efficiency, a preliminary conclusion was made about the need to conduct an adequate diagnosis of the causes of chronic infertility in cows. An innovative methodology for using differential diagnosis of key organs of the reproductive system with the palpation is presented in Figure 1.

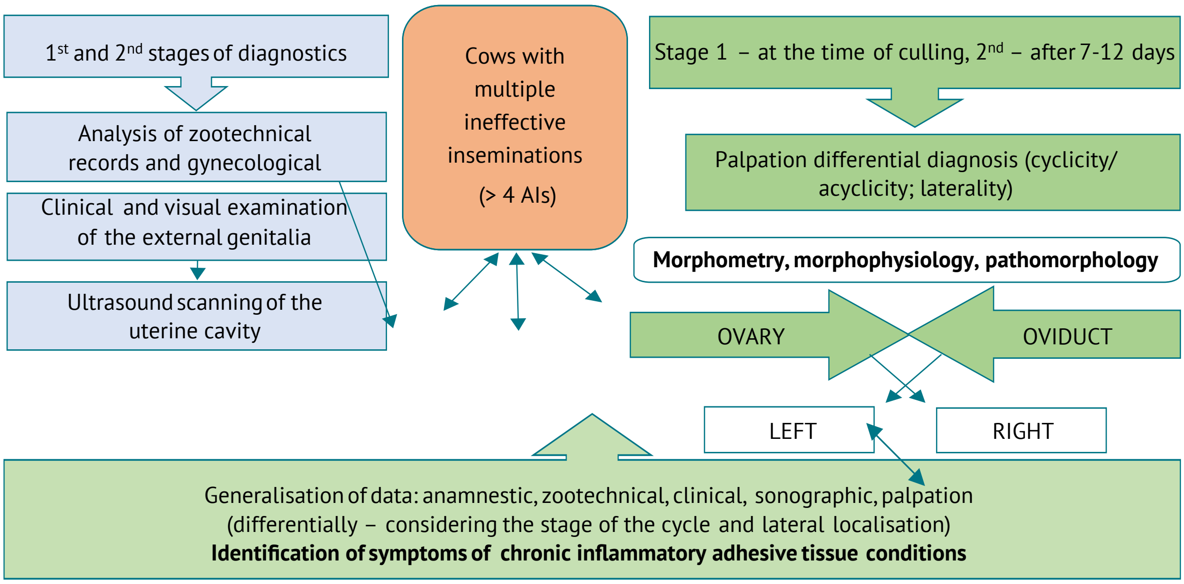

***Figure 1**. Methodical scheme of conducting a scientific and production experiment in a group of cows with chronic infertility*

The experimental group of cows was formed on the principle of "small herd" – cows aged from the 1st to the 8th lactations, of normal fatness were selected for examination, the first examination was carried out immediately after culling (according to anamnesis, namely: 4 or more infertile artificial inseminations (AIs) were performed). The data of the general gynecological examination (clinical and visual observation of the external genitalia, ultrasound scanning of the uterine cavity to exclude pregnancy and pathological exudate) were conducted. Cows with symptoms of acute or subacute inflammatory pathologies of the uterus were excluded from the experimental group, which included only animals with visually asymptomatic (latent) chronic infertility.

Using the method of periods, each cow was examined palpably twice: at the time of culling and after 10-12 days, which made it possible to establish the dynamics of morphological and functional ovarian formations in cycling females, i.e., to determine the morphometric and morphological parameters of the ovaries in the follicular and luteal phases of the sexual cycle, a modified method was presented in the publication by S.O. Sidashova *et al*. (2022). The structures of the reproductive system "ovary-oviduct" was carefully palpated, considering that the oviduct canal is an inaccessible part for hardware ultrasound diagnostics, and tactile data provide a description of the symptoms of adhesive chronic inflammatory processes of various tissues and organs, namely altered physiological mobility of the ovary, deformed and compacted tissues of the oviducts and ovaries, connective tissue adhesions and altered organ contours (Figs. 2 and 3).

Figure 2. *Macrospecimen of the reproductive system of a cow with a physiological state of the ovary-oviduc*

Notes: *Macrospecimen of the cow's reproductive system with the physiological state of the ovary-oviduct area (right-sided location): palpation of all organ contours corresponds to the anatomical norm, mobility of the ovary connection with adjacent tissues is not changed, tissue elasticity is typical, the ovary has a morphological and functional formation of the follicular phase of the cycle (maturing follicle)*

Source: *developed by the author of this study*

Figure 3. *Ovarian macrospecimen (dissected) with signs of hypotrophic state of the follicular layer*

Notes: *Macrosection of the reproductive system of a cow with chronic infertility (right-sided localisation): the anatomical contours of the organs are displaced, the tissues are hard with adhesions, and the typical ovarian mobility is not preserved. Ovary (in section) with signs of hypotrophic state of the follicular layer, no maturing follicles or functional corpus luteum, reduced morphometric size*

Source: *developed by the author of this study*

After summarising all the accumulated data (according to the sequential implementation of the survey scheme), the analytical part of the study was conducted at the Department of Surgery, Obstetrics, and Small Animal Diseases of the Faculty of Veterinary Medicine of Odesa State Agrarian University using structural-comparative and statistical methods. All experimental studies were conducted following the modern methodological approaches and corresponding requirements and standards that follow DSTU ISO/IEC 17025:2005 (2006). Animal husbandry and all manipulations were performed according to the provisions of the Procedure for conducting tests and experiments on animals by scientific institutions (Law of Ukraine No. 249, 2012), and of the European Convention for the protection of vertebrates used for experimental and other scientific purposes (1986).

RESULTS

At the first stage of the palpation study of a culled group of highly productive cows (n = 46) of the Ayrshire breed, a differential examination of the physiological or pathological state of the ovaries was performed with the identification of females with gonadopathies. Due to the presence of significant morphometric and morphological and functional differences in the size, contours, and consistency of cow ovarian tissues in different phases of the sexual cycle, the stage characteristics of the cow were immediately recorded in relation to the follicular or luteal phase formations (with additional comparison of data on zootechnical accounting of sexual activity in the last cycle for cows that showed clinical and visual cyclicality). Animals with signs of anaphrodisia and no signs of sexual cyclicity were separately identified, taking into account the symptoms of gonadopathy (Tables 1 and 2). Table 1 shows that among the 46 cows under study, 34 females with signs of the follicular phase of the sexual cycle (73.91%) were found, and there were 12 cows without cycling and corresponding functional ovarian formations (26.09%). The second stage of the study was to determine the functional state of the ovaries of females that had entered the luteal phase of the sexual cycle (palpation examination was performed 7-12 days after the previous one, Table 2).

***Table 1**. Results of in vivo diagnostics of morphofunctional or morphopathological states of ovaries of cows with multiple ineffective inseminations, n = 46 (follicular phase of the cycle)*			
Indicators		**heads**	**% (M ± m)**
Cows in the follicular phase of the cycle*	Mature (maturing) follicle	34	73.91 ± 2.93[a]
Cows with anaphrodisia, total**		12	26.09 ± 10.43[b]
Of which separate gonadopathies:	Gonadal hypotrophy	2	4.35
	Follicular cystic fibrosis***	8	17.39
	Sclerotic condition	2	4.35

***Note:** * – for females with a fixed sexual cycle; ** – for females with an acyclic state; *** – single large cysts or small multiple cysts – polycystic disease; a–b (P > 0.05)*
***Source:** developed by the authors of this study*

***Table 2**. Results of in vivo diagnostics of morphofunctional or morphopathological states of ovaries of cows with multiple ineffective inseminations, n = 46 (luteal phase of the cycle)*			
Indicators		**heads**	**% (M ± m)**
Cows in the luteal phase of the cycle*	Morphometrically and morphologically typical corpus luteum	39	84.78 ± 3.85[a]
Cows with anaphrodisia, total		7	15.22 ± 10.47[b]
Of which separate gonadopathies:	Gonadal hypotrophy	5	10.87
	Lutein cyst	0	0.00
	Sclerotic condition	2	4.35

***Note:** * – for females with a fixed sexual cycle; a–b (P > 0.05)*
***Source:** developed by the authors of this study*

At this stage of the investigation, 39 cows (84.8%) with functional ovaries were identified (a temporary endocrine gland (corpus luteum) was palpated on the right or left ovary, Fig. 4). In 5 animals (10.87%), no functional ovarian masses were palpated, which was indicative of anaphrodisiac symptoms (Fig. 5).

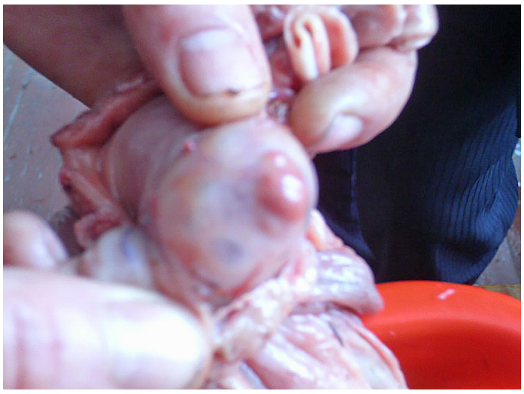

***Figure 4**. Macrosection of functionally active corpus luteum of the ovary*
***Notes:** Macrosection of the cow's reproductive system with a functional morphologically typical mid-cycle corpus luteum (physiological state of ovarian tissue)*
***Source:** developed by the authors of this study*

***Figure 5**. Macrosection of morphological structure of the active corpus luteum in the middle of the cycle*
***Notes:** Macrosection: morphological structure of the mid-cycle corpus luteum – the luteal tissue is typical in consistency and colour, the contours are clearly visible, the cavity in the middle is consistent with the physiological norm and the stage of development of the temporal gland*
***Source:** developed by the authors of this study*

Thus, differential in vivo diagnostics, considering the timing of the stages of the sexual cycle, showed that among cows culled due to chronic infertility, 73.91% had an actively functioning ovary in the follicular phase and 84.78% in the luteal phase, respectively, and there were morphological features of ovarian maturation and ovulation and preservation of the early embryo (generative and hormonal). The lateral localisation of morphological and functional formations is presented in Table 3.

***Table 3**. Lateral localisation of functional morphological formations in cows with preserved sexual cyclicity, n = 39**

Phase of the sexual cycle	Lateral localisation			
	Left ovary		Right ovary	
	heads	%	heads	%
Follicular	18	52.94	16	47.08
Luteal	21	53.8 ± 18	46.15	46.15
(M ± m)	39	53.39 ± 0.46	34	46.62 ± 0.47

***Note:** * – only cows with clinically and visually recorded sexual behaviour with physiologically appropriate timing of sexual activity periods were considered*
***Source:** developed by the authors of this study*

The in vivo diagnostic profile of the percentage frequency of various gonadopathies and morphological and functional states of the ovaries in a group of culled high-yield cows is graphically demonstrated (Fig. 6).

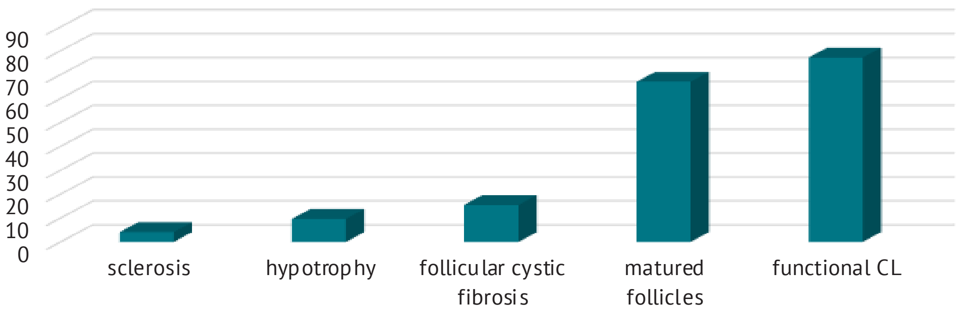

***Figure 6**. Morphofunctional/pathological profile according to in vivo palpation differential diagnosis of ovaries of cows (%) culled due to multiple ineffective inseminations, n = 46*
***Source:** developed by the authors of this study*

The ratio of ovarian functioning activity in cows both in the follicular and luteal phases of the sexual cycle, in terms of lateral location, was very close, but no correlations between the data were determined. The nature of the functional asymmetry of the ovaries indicated the presence of pathological processes in the gonadal tissues. During the study, functional formations were noted only on one side of the location: either on the left or on the right (the inactive ovary was in a hypotrophic state according to morphometric parameters). No cases of bilateral arrangement of morphofunctional formations were found. During the two stages of the study, from 4.35% to 10.87% of cases of significant hypotrophic changes in the ovarian tissues bilaterally were palpated. These pathologies have been associated with symptoms of acyclicity and chronic anaphrodisia. In this case, the ovaries were palpably reduced in size, of flattened contour, flaccid or hard consistency, with a lack of elasticity and firmness of the tissues.

In the follicular phase, 8 (17.39%) cows with cystic ovarian pathologies (single follicular cysts or polycystic ovary – multiple small cysts on the surface of the ovary) were identified. The specific feature of follicular cysticity in the group of cows studied was the palpation diagnosis of a very dense cyst membrane that did not lend itself to mechanical pressure. In the luteal phase of the cycle, no corpus luteum cysts were palpated in the group, which indicated a decrease in the level of hormonal secretion in the stage of sexual rest, namely progesterone. This may have been the cause of early embryonic death due to gonadal hormonal dysfunction, but this issue requires further investigation. In 2 females (4.35%), bilateral characteristic sclerotic changes in ovarian tissues were palpated, which completely excluded the morphological and functional activity of these organs (Fig. 7).

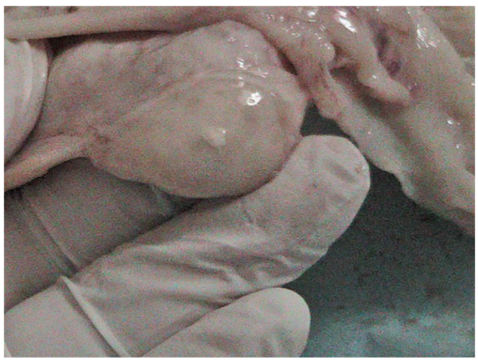

***Figure 7**. Ovarian macrosection for cows with chronic ovosalpingitis*
***Notes:** Macrosection (right lateralisation): ovary of a cow with chronic ovosalpingitis – sclerotic tissues, hard consistency, limited mobility of the organ, adhesions with the tissues of the right oviduct*
***Source:** developed by the authors of this study*

As a result of the examination, the group of culled cows was divided into two parts: the physiological state of the ovary + oviduct area and the pathological state of the tissues of this area.

Considering the lateral location of paired organs, pathological changes were distinguished as located only on one side (left or right) or bilateral localisation (Table 4).

***Table 4**. Results of differential in vivo diagnosis of symptoms of adhesive processes in the area of the reproductive tract "ovary + oviduct" in cows culled due to multiple infertile inseminations, n = 46*

Indications/symptoms	Physiological or pathological conditions of the ovary+oviduct part of the reproductive tract					
	Physiological state*		Pathomorphological condition			
			Lateral***		Bilateral	
	heads	%	heads	%	heads	%
Chronic salpingitis or its absence	22	47.83	11	23.91	13	28.26
Gonadopathies**	27	58.69	11	23.91	8	17.39
(M ± m)	68.26 ± 9.57^{a}		23.91 ± 0.00^{b}		22.83 ± 5.44^{c}	

***Note:** * – morphological and functional ovarian formations (follicle or corpus luteum); ** – including pathological conditions of the ovaries with hypotrophic or degenerative tissue changes (severe hypotrophy, cysticity, sclerotic changes); a–b (P < 0.05)*
***Source:** developed by the authors of this study*

In 22 cows (47.83%), palpation did not reveal any adherent chronic changes in the oviductal tissues, which suggests potential patency of the organ cavity for gametes and zygotes. In 11 and 13 cows (23.91% and 28.26%, respectively), characteristic adhesive changes in the structure of organs and tissue elasticity were palpated. Thus, 52.17% of the culled cows had no or little chance of physiological pregnancy, and it is likely that multiple artificial inseminations were unnecessary and only increased semen costs. The diagnosis of unilateral conditions of chronic salpingitis should have alerted veterinarians to the presence of chronic inflammatory processes in the deep parts of the genital tract, which substantially reduce the efficiency of insemination. The established symptoms of in vivo diagnostics had positive correlations between the indicators (P < 0.05). Comparison of milk production for the best lactation in the group of culled cows showed a high probability of the influence of chronic infertility on the premature retirement of dairy cows with the best breeding potential (Table 5).

***Table 5**. Milk production of cows culled due to multiple infertile inseminations, n = 46*

Groups based on in vivo diagnostic results	Number of cows		Performance in the group for the best lactation, kg of milk
	heads	%	
Symptoms of chronic salpingitis (ovosalpingitis) identified*	24	52.17	$8,928.75 \pm 411.75^{b}$
No symptoms of adhesive processes identified*	22	47.83	$6,972.14 \pm 218.11^{a}$

***Note:** * – palpatory differential diagnosis in vivo in the area of the reproductive tract "ovary+oviduct" with lateral localisation of adherent tissue conditions; a–b (P < 0.01), at õ = 1023.91; CV = 14.688; td = 2.969*
***Source:** developed by the authors of this study*

In 22 cows (47.83%) from the group of culled cows due to repeated ineffective inseminations, chronic adherent salpingitis (ovosalpingitis) was not palpably detected by in vivo diagnostics. The average milk yield for the best lactation in these females was 6,972 kg of milk. In the group with a milk yield of 8,928 kg (+28.05%; P < 0.01) for the best lactation, all cows were diagnosed with irreversible infertility caused by chronic adherent salpingitis (ovosalpingitis). That is, in 52.17% of cows, gynaecological diseases became chronic and led to adhesive pathologies in the ovary + oviduct, which resulted in irreversible infertility of high-yield cows.

DISCUSSION

Based on the correlation of data from zootechnical accounting of milk production for better lactation in the group of Ayrshire cows culled due to chronic infertility, the authors concluded that the reproductive system of high-yeild cows is much more vulnerable. Probably due to a decrease in the natural resistance and polymorbidity of the organism of high-yeild cows, gynecological inflammatory diseases in them become chronic, diffuse through the haematogenous and lymphogenous pathways into the deep layers of the reproductive tract, which causes for the development of adhesive processes in the tissues, namely chronic salpingitis and ovosalpingitis. In the group of cows, which on average had a higher expectation of better lactation, 28.05% (8,928.75 kg) of each female was diagnosed with symptoms of adherent salpingitis ($P < 0.01$), which excluded the participation of their genotypes in the further selection progress of the herd. K.M. Glosson *et al.* (2020) and S. González Moreno *et al.* (2022) obtained comparable results when assessing the reproductive potential of a dairy cow herd.

In the group of cows with lower productivity for better lactation (6,972.14 kg), no symptoms of adherent chronic salpingitis were detected during the study, which indicated the need to investigate the factors that contributed to the culling of these females due to repeated infertile inseminations in greater detail. Thus, based on the results of differential in vivo diagnostics of pathological tissue conditions in the ovary+oviduct, the researchers identified one of the factors of reducing the supply of breeding heifers with high productive potential to the herd due to premature retirement of cows with the best genotypes. In the surveyed farm, when using sperm from valuable Ayrshire sires (with a sire's mother's milk yield of 14,000-15,000 kg per lactation), no increase in dairy herd productivity was observed for a long period (about 10 years).

According to R.K. Kasimanickam and V.R. Kasimanickam (2020), extending the production life of dairy cows and increasing milk yields stays a vital component of the genetic improvement of dairy cattle in all developed countries. For both breeding and production, the most valuable animals are those that successfully combine the characteristics of long-term productive use with high milk yield and economic efficiency. Excessive early retirement of high-yielding cows that do not produce enough daughters to replenish the herd leads to the elimination of the best genotypes from the breed's gene pool, which results in large economic losses for the industry as a whole. The application of the differential palpation diagnostics proposed by the authors of the study enables zooveterinary specialists of farms to carry out preventive work and improve therapeutic gynaecological schemes to reduce the loss of highly productive cows due to chronic inflammatory gynaecological diseases.

The results of the diagnosis of 17.39% of follicular cysticity detection are alarming, which may suggest a hormonal imbalance in the body of highly productive cows, especially considering the absence of corpus luteum cysts. It is probable that hormonal dysfunctions in cows can be observed during the period from the stage of sexual cycle excitation to the stage of sexual rest, which may be a consequence of a violation of protein and fat metabolism due to a deficiency of a number of biologically active components of the diet (vitamins, microelements, etc.). The findings obtained by R. Lapp *et al.* (2020) confirm the experimental data presented in the current study and suggest that the problem of degenerative cystic changes in the gonads of cows and heifers has been understudied.

The detection of 4.35% of cases of sclerotic changes in ovarian tissue based on the studies indicated long-term inflammatory processes in the gonads and adjacent organs that were latent and not covered by therapeutic intervention in time. Usually, females with this pathology are kept in artificial insemination groups for a long time, but the significant costs of sperm doses in these cases stay useless and substantially increase the cost of the final product of dairy production. S.S. Pérez-Marín *et al.* (2023) and X. Xu *et al.* (2023) obtained analogous results when conducting repeated infertile inseminations of cows, which considerably increased the cost of the products obtained.

According to S. Sidashova *et al.* (2022), it was clinically and gynecologically established that imported cows more often have ovarian dysfunction, accompanied by pathology of the uterus and oviduct. The most common diagnosis is ovarian hypofunction. Moreover, ovarian hypofunction can occur in 73% of cows against the background of pathologies of other organs. This pathology is evidenced by signs of prolonged anaphrodisia and irreversible atrophy of the uterus and ovaries. The data obtained by the scientists showed that ovarian hypofunction is the most common gynecological disease of high-yielding cows of different breeds. According to T. Tasara *et al.* (2023), K. Khoirani and I. Karni (2023), the principal causes of ovarian dysfunction are unbalanced feeding and unfavourable housing conditions. The results of the current studies showed hypotrophic ovarian tissue lesions in high-yield cows in 4.35% and 10.87% of cases, which indicated considerable plasticity of organs for restorative trophic processes in cows that stop giving energy and nutrients to milk secretion.

Veterinary reproductive specialists C.R. Seely *et al.* (2021) and K. Tanimura *et al.* (2022) discuss the effectiveness of in vivo diagnosis of physiological or pathological conditions of the cow's ovaries, specifically during palpation. Current studies have proven sufficient prognostic efficiency of differential palpation of cow gonads in vivo, with a simultaneous positive factor of promptness in determining the symptoms of pathologies subject to therapeutic intervention. Thus, Ukrainian researchers H. Hryshchuk *et al.* (2023) found that tissues of cows with a chronic anaphrodisia exhibit characteristic pathologies, namely: a considerable reduction in gonadal size, absence of corpus luteum, primary follicles are located singly, some of them have a curved shape, vesicular follicles show uneven growth of follicular cells, complete or partial absence of follicular layer folding and lutealisation of theca cells. This was indicative of the course of chronic dystrophic processes observed in vivo during our study to determine morphometric and morphofunctional parameters. The conclusion on the histological determination of the presence of blood vessel sclerosis in the tissues of the follicular layer suggests a violation of the haemodynamics of organ function and a decrease in the trophism of the tissues of the generative and secretory layers. The formation of collagen fibres in blood vessels, according to researchers, can lead to a decrease in their elasticity, a decrease in the nutritional function of ovarian tissues, which was confirmed by the nature of the palpation data of the present study. The issue of differentiating in vivo morphological differences in the symptoms of cow ovarian hypotrophy or hypoplasia stay controversial, but this difference cannot affect the correctness of therapeutic regimens (Sidashova *et al.*, 2024).

The establishment of in vivo symptoms of adhesive changes in ovarian tissues, which is often accompanied by larger adhesive processes together with the adjacent ovary, is insufficiently revealed in the literature, and therefore the present study has been the first to show the prognostic value of irreversible infertility in cows with morphologically destroyed ovarian patency, which results in the accumulation of negative effects of the selection of the best genotypes of dairy breeds.

CONCLUSIONS

Using a differential two-stage palpation technique in a group of high-yeild Ayrshire cows (n = 46), which were culled due to repeated ineffective inseminations, 52.17% of cases of chronic adhesive salpingitis were diagnosed (23.91% – unilateral localisation – left or right; 28.26% – bilateral), which highlighted the causes of irreversible infertility of females due to the loss (complete or partial) of oviductal patency for gametes and zygotes. Cows with symptoms of irreversible infertility had significantly higher milk production (8,928.75 kg) compared to those without such symptoms (6,972.14 kg; $P < 0.01$), which indicated a greater vulnerability of high-yield cows to chronic gynecological pathologies of a latent nature.

Experimentally, in vivo palpatory diagnostics in real time highlighted the causes of multiple infertile inseminations in 52.17% of high-yielding cows, which were directly related to chronic irreversible gynecological pathology that arose as a result of incorrect use of therapeutic regimens earlier after calving, at the stage of acute and subacute endometritis. The applied method of differential in vivo palpation diagnostics allows correcting gynecological treatment regimens in a dairy farm to reduce the effects of chronic inflammatory pathological processes of the mucous membranes of various parts of the reproductive tract, specifically, deep areas of the oviduct-ovary, which is poorly interpreted.

In the group of culled cows with chronic infertility, 73.91% of functioning ovaries were diagnosed (in the follicular phase of the sexual cycle) and 84.78% – in the luteal phase, which indicated the preserved generative and hormonal status of culled cows potentially suitable for donating embryos (genetic resources). In the group of culled cows, the following gonadopathies were found: follicular cysticity – 17.39%; ovarian sclerosis – 4.35%; hypotrophy of significant severity – 4.35-10.87%, which together aggravated other gynaecological chronic pathologies. The findings of the study showed that the use of differential in vivo palpation diagnostics can contribute to the development of more effective therapeutic gynecological regimens and reduce wasted sperm and veterinary drugs after prompt diagnosis of symptoms of irreversible infertility due to adhesive processes in the ovary+oviduct section of the reproductive tract.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Анотація. Непліддя корів та телиць було і залишається найбільш актуальною проблемою скотарства. Статеві органи і молочна залоза несуть підвищене функціональне навантаження, яке пов'язане з вагітністю, родами і лактацією. Метою науково-виробничого дослідження було визначення поширення симптомів хронічної незворотної неплідності у корів айрширської породи, вибракованих внаслідок багатократних штучних осіменінь. У ході дослідження було застосовано аналітичний, структурно-порівняльний і статистичний методи, а також послідовно використано впродовж двох етапів модифіковану диференційну пальпаторну діагностику клінічного стану органів репродукції у ділянці «яєчник+яйцевід» з латеральною локалізацією. Результати дослідження показали, що корови, у яких in vivo діагностовано симптоми хронічних злипливих сальпінгітів та овосальпінгітів (52,17 %), тобто незворотну форму неплідності, мали достовірно вищу (+28,05 %; P < 0,01) молочну продуктивність за кращу лактацію, у порівнянні з тими, у яких цих патологій не встановлено. Крім того в групі вибракованих внаслідок численних неефективних осіменінь корів було виявлено суміжні гонадопатії: від 4,35 до 10,87 % виражено гіпотрофічних станів яєчників, 4,35 % симптомів склерозу гонад і 17,39 % випадків кістозних фолікулярних дегенерацій. У 73,91 % самиць було встановлено наявність статевої циклічності з незміненою функцією яєчників у фолікулярну фазу та у 84,78 % – у лютеїнову фазу циклу. Застосування в умовах виробництва диференційної пальпаторної діагностики дозволяє в умовах in vivo прогнозувати тенденцію до втрати генетичних ресурсів (здатності яєчниками корів зберігати генеративну і секреторну функції) у високопродуктивних корів внаслідок хронізації запальних гінекологічних патологій, що сприятиме удосконаленю медикаментозних і біотехнологічних схем терапевтичних заходів з профілактики неплідності поголів'я дійного стада

Ключові слова: молочні корови; генетичні ресурси; хронічна неплідність; яєчники; яйцеводи; хронічні запальні гінекологічні процеси; сальпінгіти; спайки

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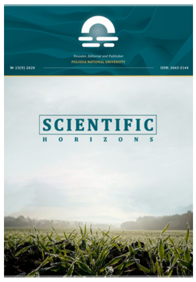

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Study of antibiotic resistance of Salmonella strains forming biofilm

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Abstract. The aim of the study was to investigate the prevalence and resistance of biofilm-forming Salmonella strains on poultry farms in Kazakhstan, Latvia, and Turkey. During the study, samples of faeces, tissues (liver and intestines) and water from drinkers were collected and analysed from January to December 2023. Salmonella strains were isolated and identified using standard microbiological methods. A total of 150 Salmonella strains were isolated and identified, of which 90 strains were obtained from faecal samples, 40 from tissue samples and 20 from water samples. The distribution of strains by country showed that in Kazakhstan, Latvia and Turkey, the

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largest number of strains were isolated from faecal samples. Of the 80 *Salmonella Enteritidis* strains, most showed the ability to form biofilms, as determined by the crystal violet method, with subtypes SE1 and SE2 showing the highest propensity for biofilm formation. Among the *Salmonella Typhimurium* strains, a significant biofilm formation ability was found in the ST1 subtype. Antibiotic resistance was determined using the disc diffusion method. The biofilm-forming strains showed higher antibiotic resistance compared to the non-biofilm-forming strains. Of the 150 strains isolated, 105 showed resistance to at least one of the antibiotics tested, with the highest level of resistance among *Salmonella Typhimurium* strains. Correlation analysis revealed a significant positive relationship between the level of biofilm formation and antibiotic resistance. The results demonstrate the need to introduce the development of new methods of control and prevention of infections on poultry farms, which would take into account the peculiarities of biofilm formation and antibiotic resistance of certain strains

Keywords: faecal samples; serotype; genetic factor; multidrug resistance; poultry farming

INTRODUCTION

The study of the problem of antibiotic resistance of Salmonella and their ability to form biofilms on poultry farms is critical to ensure food safety and animal health. Antibiotic resistance is a global threat that complicates the treatment of infectious diseases and increases the risk of spreading resistant pathogens. Biofilms formed by bacteria exacerbate this problem by creating a protective barrier that makes bacteria less susceptible to antibiotics and disinfectants. The need for the study is driven by the threat posed by resistant strains of Salmonella, especially in the context of agricultural production in Kazakhstan, Latvia, and Turkey. These countries are actively developing agriculture, particularly poultry farming, which makes the problem of antibiotic resistance and biofilm formation particularly relevant.

The importance of the problem of antibiotic resistance is confirmed by the World Health Organization (WHO) (2018). According to the WHO, millions of people around the world are infected with salmonellosis every year, and a significant proportion of these infections are caused by antibiotic-resistant strains. The WHO notes that the ability of bacteria to form biofilms makes treatment of infections much more difficult and increases the risk of long-term survival of pathogens in the environment (Bal-Prylypko *et al.*, 2023). This highlights the need to develop global strategies to control and prevent the spread of resistant strains. The European Food Safety Authority and the European Centre for Disease Prevention and Control (2022) also conducted studies aimed at monitoring antibiotic resistance in Salmonella in Europe. In 2020, the European Food Safety Authority published reports showing that the level of resistance to ampicillin and tetracycline has increased by 15% over the past five years. The European Food Safety Authority also emphasizes the importance of biofilms in resistance mechanisms and recommends further research to develop effective methods to combat this problem.

In Kazakhstan, the problem of antibiotic resistance and biofilm formation in Salmonella is being actively studied. R. Rychshanova *et al.* (2021) found that 60% of strains isolated from poultry farms were multidrug-resistant, including ampicillin, tetracycline, and trimethoprim/sulfamethoxazole. Studies by A. Mendybayeva *et al.* (2022) also showed that biofilms play a pivotal role in increasing this resistance by creating a protective barrier that hinders the penetration of antibiotics. However, their work did not investigate in sufficient detail the specific genetic mechanisms underlying biofilm formation and their impact on resistance, which requires further research to understand these processes in local conditions.

The life cycle of Salmonella is characterized by alternating stages of host colonization and adaptation to environmental conditions. These aspects have been studied in detail by D. Zhanabayeva *et al.* (2021) and K. Mogilev *et al.* (2023). To successfully survive in the environment, *Salmonella spp.* have evolved a number of adaptive strategies, including adhesion to surfaces and the formation of biofilms. Biofilms consist of tightly-knit communities of bacteria, which may include one or more species, firmly attached to each other and to various surfaces. The formation of biofilms depends on many factors, including the interactions between bacteria within the consortium, the type and chemical properties of the surface to which they are attached, and the general environmental conditions (Liu *et al.*, 2023).

In Latvia, M. Terentjeva *et al.* (2017) conducted studies showing a high prevalence of resistant Salmonella strains on poultry farms. About 70% of poultry faecal samples contained Salmonellae resistant to several antibiotics, including ampicillin and tetracycline. In their study, E. Bartkiene *et al.* (2020) identified the csgD and adrA genes that contribute to the formation of biofilms and increase antibiotic resistance. However, their work does not take into account the influence of different environmental conditions on biofilm formation, nor does it investigate the influence of other possible genes, which leaves gaps in understanding the full picture of resistance.

In Turkey, the problem of antibiotic resistance of Salmonella is also relevant, especially in the context of intensive agricultural development. A. Arkali and

B. Çetinkaya (2020) showed that a significant proportion of Salmonella strains isolated from poultry farms are highly resistant to antibiotics such as ampicillin, chloramphenicol, and ciprofloxacin. N. Saricam and M. Akan (2023) identified the bcsA and pgaABCD genes, which play a major part in the synthesis of the extracellular matrix of biofilms, contributing to antibiotic resistance. However, their study does not sufficiently cover the possible ways of transferring resistance genes between strains and their impact on different stages of biofilm formation, which requires additional research.

The aim of this study was to investigate the prevalence and resistance of biofilm-forming Salmonella strains on poultry farms in Kazakhstan, Latvia, and Turkey. The objectives of this study were to identify and characterize Salmonella strains isolated from faecal, tissue and water samples, analyse the presence of genes associated with biofilm formation and antibiotic resistance, and assess the level of resistance to various antibiotics.

MATERIALS AND METHODS

The study was conducted in three laboratories: Central Reference Laboratory for Infectious Disease Monitoring in Almaty, Kazakhstan, the Reference Laboratory for Infectious Diseases in Riga, Latvia, and the National Laboratory for Monitoring Zoonotic Infections in Ankara, Turkey, from January to December 2023. Samples were collected from poultry farms in different regions of Kazakhstan, Latvia, and Turkey. The sample included faecal samples, tissue samples and water samples. Faecal samples were collected from the chicken houses using sterile containers and transported to the respective laboratories at 4°C, where they were stored at -20°C until analysis. Tissue samples included liver and intestine samples from birds slaughtered for diagnostic purposes and were transported in the same manner as faecal samples. Water samples from bird drinkers were collected in sterile bottles and stored at 4°C until analysis. The procedure for collecting, transporting, storing samples, as well as conducting all experiments was the same for all three countries, which ensured comparability of data and uniform research standards.

Standard microbiological methods were used to isolate and identify Salmonella strains. Samples were pre-homogenised and diluted in sterile physiological water. They were then inoculated onto selective agar media (XLD agar) and incubated at 37°C for 24-48 hours. Suspicious colonies growing on the agar were tested for biochemical properties, including glucose, lactose, urease fermentation and the presence of hydrogen sulphide. For final identification, serological tests using agglutination with antiserum were used. All manipulations were carried out in laminar flow cabinets to ensure sterility.

The ability of the strains to form biofilms was assessed by the crystal violet staining method. Pure cultures of Salmonella were inoculated into 96-well microplates containing LB nutrient medium and incubated at 37°C for 24 hours. After incubation, the contents of the wells were removed, and the biofilms were fixed with methanol for 15 minutes. Then they were stained with 0.1% crystal violet solution for 15 minutes and washed with distilled water three times. The intensity of the staining was measured spectrophotometrically at 570 nm, evaluating the biofilm formation on a scale (weak, moderate, strong). This method allowed accurately identifying the degree of biofilm formation, which is critical for understanding bacterial resistance.

Antibiotic susceptibility was assessed by the Kirby-Bauer disco-diffusion method and the microbial reconnaissance method. For the disco-diffusion method, pure Salmonella cultures were inoculated on Mueller-Hinton agar, after which antibiotic-impregnated discs (ampicillin, chloramphenicol, ciprofloxacin, tetracycline, trimethoprim/sulfamethoxazole) were placed on the agar and incubated at 37°C for 24 hours. The diameters of the growth inhibition zones were measured, and the strains were classified as sensitive, intermediate, or resistant according to the Clinical & Laboratory Standards Institute (CLSI) criteria. According to these criteria, the thresholds for the antibiotics used are as follows: For ampicillin, sensitive strains have a growth inhibition zone diameter of ⩾17 mm, intermediate strains – 14-16 mm, and resistant strains – ⩽13 mm; for ciprofloxacin, sensitive strains have a growth inhibition zone diameter of ⩾21 mm, intermediate strains – 16-20 mm, and resistant strains – ⩽15 mm; for chloramphenicol, sensitive strains have a growth inhibition zone diameter of ⩾18 mm, intermediate strains – 13-17 mm, and resistant strains – ⩽12 mm; for trimethoprim/sulfamethoxazole, sensitive strains have a growth inhibition zone diameter of ⩾16 mm, intermediate strains have a diameter of 11-15 mm, and resistant strains have a diameter of ⩽10 mm; for tetracycline, sensitive strains have a growth inhibition zone diameter of ⩾15 mm, intermediate strains have a diameter of 12-14 mm, and resistant strains have a diameter of ⩽11 mm. These thresholds are used to determine the effectiveness of antibiotics against the tested Salmonella strains. The microbial exploration method was used to determine the minimum inhibitory concentrations for each antibiotic using standard broth microbial exploration methods. These methods provided accurate data on the resistance of the strains to different antibiotics.

SPSS software was used to analyse the data. The χ^2 test was used to evaluate differences in resistance levels between biofilm-forming and non-biofilm-forming strains. Correlation analyses were performed to identify the relationship between biofilm formation and antibiotic resistance levels. The Student's t-test and Mann-Whitney U-test were also used to compare mean values and rank data, respectively. These statistical methods allowed determining significant differences and dependencies, which is critical for understanding the mechanism of resistance and developing effective strategies to combat Salmonella. All experimental studies were conducted in accordance with European convention for the protection of vertebrate animals used for experimental and other scientific purposes (1986).

RESULTS

The study isolated and identified 150 strains of Salmonella from samples collected from poultry farms in Kazakhstan, Latvia, and Turkey. The samples included faeces, tissues (liver and intestines) and water from drinkers. Of the 150 isolated strains, the largest number (90 strains) were obtained from faecal samples, indicating a high prevalence of Salmonella in the intestines of birds. The high percentage of strains isolated from faeces may indicate intensive colonization of the intestinal tract of birds by Salmonella, which is an important epidemiological factor, given that faeces can easily contaminate the environment and feed, creating conditions for the spread of infection among birds and other animals, as well as for potential human infection through contaminated food.

Faecal samples were isolated from 35 strains in Kazakhstan, 30 strains in Latvia and 25 strains in Turkey. The remaining strains were isolated from tissue samples (40 strains) and water samples (20 strains), indicating that the bacteria may be spread through the environment and biological tissues of birds. Tissue samples included 15 strains in Kazakhstan, 12 strains in Latvia and 13 strains in Turkey. The isolation of Salmonella from the liver and intestines confirms their ability to penetrate and infect various organs of birds, which can lead to systemic infections and deterioration in the overall health of birds. Infection in the liver can be particularly dangerous, as this organ plays a key role in metabolic processes and detoxification. An infection in the intestine can disrupt digestion and nutrient absorption, which also negatively affects the health and performance of birds. The isolation of Salmonella from water samples (20 strains) indicates possible contamination of water bodies and watering troughs on poultry farms. Water is an indispensable element in the life of poultry, and its contamination can contribute to the spread of infection among the flock. Seven strains were isolated from water samples in Kazakhstan, eight strains in Latvia and five strains in Turkey. The presence of Salmonella in water may indicate inadequate sanitation and hygiene on farms, which requires improved water management and watering systems to prevent the spread of pathogens (Table 1).

***Table 1**. General identification of Salmonella strains forming biofilm in the Republic of Kazakhstan, the Republic of Latvia and the Republic of Turkey*

Source of the sample	Faeces	Fabrics	Water	Total
Total number of strains	90	40	20	150
Salmonella enteritidis	50	20	10	80
SE1 subtypes	20	8	5	33
SE2 subtypes	15	6	3	24
SE3 subtypes	10	4	1	15
Other SE subtypes	5	2	1	8
Salmonella Typhimurium	25	10	5	40
ST1 subtypes	10	4	2	16
ST2 subtypes	8	3	1	12
ST3 subtypes	5	2	1	8
Other subtypes of ST	2	1	1	4
Other serotypes	15	10	5	30

***Source:** developed by the authors*

The study found that the most common serotypes were *Salmonella Enteritidis* and *Salmonella Typhimurium, as* evidenced by their frequent isolation from all types of samples. *Salmonella Enteritidis* was present in 53.3% of cases, while *Salmonella Typhimurium* was present in 26.7%. The remaining 20% were other Salmonella serotypes. The largest number of strains were isolated from faecal samples, indicating a high prevalence of Salmonella in the intestines of poultry. The isolated strains were identified and confirmed by serological methods, which allowed accurately determining their belonging to specific serotypes and subtypes.

Detailed analyses showed that *Salmonella Enteritidis* strains were dominated by subtypes SE1, SE2 and SE3. These subtypes were detected in all types of samples, with the highest number of SE1 and SE2 subtypes detected in faecal samples, which may indicate their important role in poultry enteric infections. The SE3 subtype was represented by fewer strains, which may indicate its less significant role or rarer distribution. Similarly, among the *Salmonella Typhimurium* strains, ST1, ST2 and ST3 subtypes dominated. The ST1 subtype was the most frequently detected in faecal samples, which may indicate its high virulence and ability to colonize the intestines of birds. Subtypes

ST2 and ST3 were also detected in all types of samples, but in lower amounts, indicating their presence, but lower prevalence compared to subtype ST1. These results indicate the significant role of *Salmonella Enteritidis* and *Salmonella Typhimurium* in poultry infections and the need for further study of these serotypes and their subtypes to develop effective control and prevention measures.

A major part of the study was to evaluate the ability of the isolated Salmonella strains to form biofilms. Out of 150 isolated and identified Salmonella strains, 90 (60%) showed the ability to form biofilms. These strains were distributed as follows: 55 strains of *Salmonella* Enteritidis, 25 strains of *Salmonella Typhimurium* and 10 strains of other serotypes.

***Table 2**. Ability of selected Salmonella strains to form biofilms*

Serotype and subtype	Total number of strains	Number of strains forming biofilms	Percentage of strains forming biofilms
Salmonella Enteritidis	80	55	68.75%
SE1	33	24	72.73%
SE2	24	18	75%
SE3	15	10	66.67%
Other SE subtypes	8	3	37.5%
Salmonella Typhimurium	40	25	62.5%
ST1	16	12	75%
ST2	12	7	58.33%
ST3	8	4	50%
Other subtypes of ST	4	2	50%
Other serotypes	30	10	33.33%
Total	150	90	60%

***Source:** developed by the authors*

Of the 80 strains of *Salmonella Enteritidis*, the majority showed the ability to form biofilms. The SE1 and SE2 subtypes showed the highest propensity for biofilm formation, with the vast majority of strains forming stable biofilms. The SE3 subtype was also capable of biofilm formation, but to a lesser extent than SE1 and SE2. Other SE subtypes showed significantly less biofilm formation ability, which may indicate differences in their genetic structure. The distribution of *Salmonella Enteritidis* strains by country is as follows: in Kazakhstan, 20 out of 30 strains formed biofilms, with the highest tendency to biofilm formation shown by subtypes SE1 and SE2. In Latvia, 18 out of 25 strains formed biofilms, with the predominance of SE1 and SE2 subtypes. In Turkey, 17 out of 25 strains formed biofilms, also with a predominance of SE1 and SE2 subtypes.

Among the *Salmonella Typhimurium* strains, a significant ability to biofilm formation was found in the ST1 subtype, which emphasizes its potential virulence and ability to survive in adverse conditions. Subtype ST2 showed a moderate ability to biofilm formation, while subtype ST3 and other subtypes showed a lower tendency to this process, which may indicate the presence of different mechanisms for regulating biofilm formation. The distribution of *Salmonella Typhimurium* strains by country is as follows: in Kazakhstan, 12 out of 15 strains formed biofilms, with the ST1 subtype being the most common. In Latvia, 10 out of 13 strains formed biofilms, with the ST1 subtype predominating. In Turkey, 10 out of 12 strains formed biofilms, also with the dominance of the ST1 subtype.

Specific features of biofilm formation of certain strains in each country include the following observations: in Kazakhstan, *Salmonella Enteritidis* and *Salmonella Typhimurium* strains that formed biofilms were the most resistant to adverse conditions, which may be related to specific environmental and management factors on farms. In Latvia, biofilm-forming strains showed high adhesion and resistance to disinfectants, indicating the need for improved sanitation practices. In Turkey, biofilm-forming strains showed high survival in different environmental conditions, which may be due to adaptation to local climatic conditions. These data emphasize the importance of monitoring and controlling biofilm-forming Salmonella strains in different countries. The high biofilm-forming capacity of certain subtypes of *Salmonella Enteritidis* and *Salmonella Typhimurium* requires special attention when developing strategies for the control and prevention of salmonellosis. Given the differences in the genetic and phenotypic characteristics of strains in different countries, control, and prevention approaches should be adapted to the specific conditions of each country.

The distribution of biofilm formation ability among all isolated strains showed that *Salmonella Enteritidis* and *Salmonella Typhimurium* strains have a higher tendency to biofilm formation compared to other serotypes. This may indicate their increased virulence and ability to survive in adverse conditions. The biofilms formed by these strains are highly resistant to external influences, including antibiotics and disinfectants, which makes them more difficult to control. The ability of Salmonella strains to form biofilms largely depends on the presence and expression of certain genes. The most important genetic factors include genes responsible for adhesion and colonization, such as fimA, lpfC and agfA, which encode fimbriae and adhesins that help bacteria attach to surfaces. Genes regulating extracellular matrix synthesis, such as csgD, bcsA and pgaABCD, control the synthesis of extracellular polysaccharides and other biofilm matrix components. Genes related to the regulation of biofilm formation, including the global regulators rpoS, c-di-GMP and quorum sensing systems (e.g. luxS), play a key role in coordinating biofilm formation in response to external signals and stress conditions.

In addition to genetic factors, environmental conditions such as temperature, nutrient availability, the presence of antimicrobial agents and physical surface properties also have a significant impact on biofilm formation (Pyatkovskyy, 2023). For example, low temperatures stimulated the formation of biofilms in some strains, while high temperatures can inhibit this process. These findings highlight the importance of biofilm formation as a factor contributing to the survival and spread of pathogens in poultry farms. The high ability of *Salmonella* Enteritidis and *Salmonella Typhimurium* strains to form biofilms requires special attention when developing strategies for the control and prevention of salmonellosis in poultry farming. Given the ability of biofilms to protect bacteria from antibiotics and disinfectants, it was essential to develop and implement methods aimed at destroying biofilms and preventing their formation. The results highlight the need for further study of genetic and phenotypic factors affecting the ability of Salmonella strains to form biofilms. This study provides important data for the development of more effective control and prevention measures for Salmonellosis on poultry farms, which ultimately contributes to improved poultry health and food safety.

Of the 150 Salmonella strains isolated, 105 (70%) showed resistance to at least one of the antibiotics tested. Of these, 60 (40%) were multidrug-resistant, i.e. resistant to three or more antibiotics. The highest level of resistance was observed among *Salmonella Typhimurium* strains (Table 3).

***Table 3**. Indicators of antibiotic resistance of selected Salmonella strains*

Antibiotic	*Salmonella Enteritidis* (%)	*Salmonella Typhimurium* (%)	Other serotypes (%)
Ampicillin	43.75 (35)	62.5 (25)	23.33 (7)
Chloramphenicol	18.75 (15)	25 (10)	10 (3)
Ciprofloxacin	12.5 (10)	37.5 (15)	6.67 (2)
Tetracycline	56.25 (45)	75 (30)	16.67 (5)
Trimethoprim/ sulfamethoxazole	37.5 (30)	50 (20)	13.33 (4)
Multi-drug resistant strains	37.5 (30)	62.5 (25)	10 (3)

***Source:** developed by the authors*

Of the 150 Salmonella strains isolated in Kazakhstan, Latvia and Turkey, 105 (70%) showed resistance to at least one of the antibiotics tested. Of these, 60 (40%) were multidrug-resistant, i.e. resistant to three or more antibiotics. The highest level of resistance was observed among *Salmonella Typhimurium* strains. Out of 80 *Salmonella Enteritidis* strains, 60 (75%) showed resistance to one or more antibiotics. The most common resistance was to tetracycline (45 strains). High levels of resistance were also observed to ampicillin (35 strains) and trimethoprim/sulfamethoxazole (30 strains). The lowest number of strains showed resistance to ciprofloxacin (10 strains) and chloramphenicol (15 strains). Within this group, multidrug resistance was observed in 30 strains.

Out of 40 strains of *Salmonella Typhimurium*, 35 (87.5%) showed resistance to one or more antibiotics. The most common resistance was to tetracycline (30 strains) and ampicillin (25 strains). A high level of resistance was also observed to trimethoprim/sulfamethoxazole (20 strains). Resistance to ciprofloxacin (15 strains) and chloramphenicol (10 strains) was lower. Among these strains, multidrug resistance was observed in 25 strains. Out of 30 strains of other Salmonella serotypes, 10 (33.33%) showed resistance to one or more antibiotics. The most frequent resistance was to ampicillin (7 strains) and tetracycline (5 strains). Multidrug resistance among these strains was less pronounced compared to *Salmonella Enteritidis* and *Salmonella Typhimurium,* and amounted to 3 strains.

Resistance to ampicillin was observed in 35 strains of *Salmonella Enteritidis*, 25 strains of *Salmonella Typhimurium* and 7 strains of other serotypes. Ampicillin is frequently used to treat Salmonella infections, and its overuse may have contributed to the development of resistance. The high level of resistance to ampicillin among *Salmonella Typhimurium* strains may be due to the presence of blaTEM genes, which encode a beta-lactamase that degrades ampicillin. Resistance to chloramphenicol was less common, being observed in 15 strains of *Salmonella Enteritidis*, 10 strains of *Salmonella Typhimurium* and 3 strains of other serotypes. Chloramphenicol has been used in the past, but its use has been limited due to toxicity, which may have contributed to the persistence of susceptibility in most strains.

Ciprofloxacin remains effective against most Salmonella strains, but resistance has been identified in 10 *Salmonella Enteritidis* strains, 15 *Salmonella Typhimurium strains* and 2 strains of other serotypes. Mechanisms of resistance include mutations in the gyrA and parC genes encoding topoisomerases, which are targets of ciprofloxacin. Tetracycline was less effective, with a high level of resistance among all serotypes: 45 strains of *Salmonella Enteritidis*, 30 strains of *Salmonella Typhimurium* and 5 strains of other serotypes. Causes of resistance include the presence of tetA and tetB genes, which encode proteins that remove the antibiotic from the bacterial cell.

Resistance to trimethoprim/sulfamethoxazole has been identified in 30 strains of *Salmonella Enteritidis*, 20 strains of *Salmonella Typhimurium* and 4 strains of other serotypes. Resistance mechanisms include mutations in genes encoding enzymes targeted by trimethoprim and sulfamethoxazole. Multidrug resistance was most pronounced among *Salmonella Typhimurium* strains, where 62.5% of strains were resistant to three or more antibiotics. In *Salmonella Enteritidis* strains, this figure was 37.5%, and in other serotypes – 10%. This highlights the high threat of multidrug-resistant strains, especially among *Salmonella Typhimurium*.

Analysis of the antibiotic resistance data revealed several key trends. *Salmonella Typhimurium* strains showed the highest level of resistance to all tested antibiotics, compared to *Salmonella Enteritidis* and other serotypes. This may be due to the higher genetic plasticity and the ability of *Salmonella Typhimurium to* acquire and retain resistance genes. The high level of resistance to tetracycline and ampicillin among all Salmonella serotypes emphasizes the need to review the use of these antibiotics in veterinary practice and to develop alternative treatment methods. Tetracycline and ampicillin are often used as first-line therapy, and their overuse may have contributed to the development and spread of resistant strains. Multidrug resistance in a significant number of strains, especially in *Salmonella Typhimurium,* poses a serious threat to poultry health and potentially to humans. Multidrug-resistant strains of Salmonella are more difficult to treat and can cause more severe infections. The lower resistance to ciprofloxacin and chloramphenicol may indicate that these antibiotics retain their effectiveness against Salmonella to some extent. However, the use of these antibiotics should also be monitored to prevent the development of resistance in the future.

The findings highlight the need for further monitoring and control of antibiotic resistance among Salmonella strains on poultry farms. The development and implementation of strategies aimed at reducing antibiotic use and preventing the spread of resistant strains are critical to ensure poultry health and food safety. Additionally, understanding the genetic mechanisms underlying resistance will help to develop more effective methods of controlling these pathogens. The χ^2 test was used to evaluate differences in resistance levels between biofilm and non-biofilm strains. The results showed significant differences in resistance levels between these groups. The biofilm-forming strains showed significantly higher resistance to ampicillin, tetracycline and trimethoprim/sulfamethoxazole than the non-biofilm-forming strains. This indicates that biofilm formation plays a pivotal role in increasing bacterial resistance to antibiotics.

Correlation analysis was performed to identify the relationship between biofilm formation and antibiotic resistance. The analysis showed a significant positive correlation between the level of biofilm formation and resistance to several antibiotics. For example, the Pearson correlation coefficient between biofilm formation and resistance to tetracycline was 0.65, indicating a strong positive relationship. A similar correlation was found for ampicillin and trimethoprim/sulfamethoxazole, which points out the importance of biofilm formation in antibiotic resistance mechanisms. Student's t-test was used to compare the mean values, which showed that the mean levels of resistance to ampicillin and tetracycline were significantly higher in biofilm-forming strains than in non-biofilm-forming strains. For example, the average level of resistance to ampicillin in biofilm-forming strains was 75%, while in non-biofilm-forming strains it was 45%.

The Mann-Whitney U test was used to compare the rank data, which also confirmed significant differences between the groups. The results of the analysis showed that the ranks of resistance to tetracycline and trimethoprim/sulfamethoxazole were significantly higher in strains that formed biofilms. This further confirms that biofilm formation is an important factor influencing the level of antibiotic resistance. The results of the statistical analysis highlighted significant differences in resistance levels between biofilm-forming and non-biofilm-forming strains. These differences indicate a critical role of biofilm formation in the mechanisms of antibiotic resistance. The biofilm-forming strains have increased resistance to various antibiotics, making them more difficult to treat. Correlation analysis revealed a strong positive correlation between the level of biofilm formation and resistance to several key antibiotics, which highlights the importance of further studying the genetic and phenotypic factors that influence this process. These data provide crucial information for the development of more effective strategies for the control and prevention of salmonellosis. Implementation of measures aimed at destroying biofilms and preventing their formation can significantly increase the effectiveness of treatment and reduce the spread of resistant strains.

DISCUSSION

The study showed that a significant number of Salmonella strains were isolated from poultry faecal samples on farms in Kazakhstan, Latvia, and Turkey. The high prevalence of these bacteria in the intestines of poultry indicates a significant epidemiological threat. This is confirmed by the studies of other authors. For example, Y. Li *et al*. (2022) in Spain found that 75% of faecal samples of birds contained Salmonella. In Italy, R. Farahani *et al*. (2023) found that 80% of faecal samples from poultry farms were positive for Salmonella, confirming the intensive colonization of the intestinal tract of birds. Comparison of these results highlights the common problem of high prevalence of Salmonella in poultry faeces, indicating the need for improved sanitary conditions and enhanced on-farm controls to prevent the spread of infection.

The Salmonella Enteritidis and *Salmonella Typhimurium* strains isolated from the samples showed a significant ability to form biofilms. Of the 80 *Salmonella Enteritidis* strains, 55 formed biofilms, with subtypes SE1 and SE2 showing the highest propensity for this process. In the USA, a similar study conducted by D. Voss-Rech *et al*. (2022) showed that 70% of *Salmonella Enteritidis* strains and 65% of *Salmonella Typhimurium* strains formed biofilms on various surfaces. In Canada, N. Melo *et al*. (2023) and G. Krüger *et al*. (2023) found that more than 60% of Salmonella strains isolated from food and the environment were capable of forming biofilms. These results confirm that biofilm formation is common among Salmonella strains and highlight the need to develop methods aimed at disrupting biofilms for more effective infection control.

The biofilm-forming Salmonella strains showed higher antibiotic resistance than the non-biofilm-forming strains. Of the 80 strains of *Salmonella Enteritidis that* formed biofilms, 75% were resistant to ampicillin and 60% to tetracycline. In the UK, a study by A. Aleksandrowicz *et al*. (2023) showed that biofilm-forming *Salmonella Enteritidis* strains were 70% and 60% resistant to ampicillin and tetracycline, respectively. In Germany, similar studies conducted by A. Tiwari *et al*. (2022) and M. Farhat *et al*. (2023) found that biofilm-forming strains of *Salmonella Typhimurium* demonstrate resistance to several classes of antibiotics. These findings highlight the need to develop strategies to combat biofilms to increase the effectiveness of antibiotics.

Correlation analysis showed a significant positive relationship between the level of biofilm formation and antibiotic resistance (Kovalchuk *et al.*, 2021). The Pearson correlation coefficient between biofilm formation and tetracycline resistance was 0.65. In Japan, studies by R. Hage *et al*. (2022) and X. Shen *et al*. (2023*)* showed a similar positive correlation between biofilm formation and antibiotic resistance in *Salmonella Enteritidis* strains. In South Korea, similar results were obtained by M. Khan and S. Rahman (2022) for *Salmonella Typhimurium* strains, confirming that biofilm formation is associated with increased antibiotic resistance. These findings highlight the need for a comprehensive approach to infection control, including measures to break down biofilms and reduce antibiotic use.

The average levels of resistance to ampicillin and tetracycline were significantly higher in biofilm-forming strains, which is also confirmed by other studies. In Spain, a study *by* W. Kamal *et al*. (2023) showed that the average levels of resistance to ampicillin in biofilm-forming strains were 75% and to tetracycline 60%. In Canada, A. Kagambèga *et al*. (2022) and C. Samper-Cativiela *et al*. (2022) found that the average levels of resistance to ampicillin and tetracycline in biofilm-forming strains were also significantly higher than in non-biofilm-forming strains. These results confirm that biofilm formation is an indispensable factor in antibiotic resistance and requires the development of new methods to combat biofilms to increase the effectiveness of antibiotics.

The study also showed that biofilm formation plays a key role in the mechanisms of antibiotic resistance. In particular, *Salmonella Enteritidis* and *Salmonella Typhimurium biofilm-forming strains* showed significantly higher resistance to ampicillin, tetracycline and trimethoprim/sulfamethoxazole compared to non-biofilm-forming strains (Uzakov *et al.*, 2020). The analysis showed that 75% of the biofilm-forming *Salmonella Enteritidis* strains were resistant to ampicillin, while the figure for non-biofilm-forming strains was only 45%. A similar pattern was observed for tetracycline: 60% of the biofilm-forming strains were resistant, while the non-biofilm-forming strains had a resistance rate of 30%. This fact indicates that biofilms not only protect bacteria from external influences, but also contribute to their resistance to antibiotics, creating an additional barrier to drug penetration. In the UK, I. Igbinosa *et al.* (2023) found that biofilms protect bacteria from antibiotics, making it more difficult to treat infections. They found that strains of Salmonella that form biofilms show resistance to ampicillin and tetracycline at 70% and 60%, respectively. In China, Y. Hu *et al*. (2022) and X. Qin *et al*. (2022) confirmed that biofilms contribute to the development of antibiotic resistance, as shown by *Salmonella Typhimurium* strains, where biofilm-forming strains showed resistance to several classes of antibiotics. Comparison with the data from the above study highlights the need to introduce methods aimed at destroying biofilms to improve the treatment of bacterial infections. The results of the above study show that biofilm formation significantly complicates the treatment of infections, as bacteria in biofilms are less susceptible to antibiotics. This underscores the importance of developing new therapeutic strategies aimed at breaking down biofilms and overcoming antibiotic resistance, which will increase the effectiveness of antibiotic therapy and reduce the spread of resistant strains of Salmonella.

Antibiotic resistance among *Salmonella* strains in Kazakhstan, Latvia, and Turkey was high, especially among *Salmonella Typhimurium strains*. Of the 150 strains isolated, 105 showed resistance to at least one of the antibiotics tested, with the highest level of resistance among *Salmonella Typhimurium* strains. In Canada, W. Chen *et al.* (2023) found that 60% of Salmonella strains were resistant to ampicillin and 50% to tetracycline. The comparison shows that the problem of antibiotic resistance is global and requires a review of the use of antibiotics in veterinary medicine and the search for alternative treatments.

The study showed that biofilm formation in *Salmonella Enteritidis* and *Salmonella Typhimurium* strains is associated with the presence of certain genes, such as fimA, lpfC and agfA, which encode adhesins and fimbriae that help bacteria attach to surfaces. The strains with high levels of biofilm formation identified in the above study possessed these genes, which may have contributed to their increased resistance to antibiotics. In a study conducted by I. Ohashi *et al.* (2022) in Japan, it was found that biofilms protect bacteria from antibiotics, making the treatment of infections more difficult. They found that the strains of *Salmonella Enteritidis that* form biofilms show resistance to chloramphenicol and sulfamethoxazole at 30% and 45%, respectively. In addition, they identified the presence of the csgD and adrA genes, which played a key role in biofilm formation. In China, K. Chen *et al.* (2023) also confirmed that biofilms contribute to the development of antibiotic resistance. M. Syafitri *et al.* (2023) found that biofilm-forming strains of *Salmonella Typhimurium* demonstrate resistance to several classes of antibiotics. Their study focused on the bcsA and pgaABCD genes, which are involved in the synthesis of the extracellular matrix of biofilms. Comparison of the results of the above study with the data of global authors shows both similarities and differences. The key genes contributing to biofilm formation and antibiotic resistance were fimA, lpfC and agfA. While studies in the UK and Germany identified other significant genes such as csgD, adrA, bcsA and pgaABCD. These differences may be due to the diversity of Salmonella strains and regional distribution of genes responsible for biofilm formation and resistance.

The ambiguity of the results emphasizes the complexity of the interaction between genetic factors affecting biofilm formation and antibiotic resistance. In the above study, the detection of the fimA, lpfC and agfA genes, as well as high resistance to ampicillin and tetracycline, indicates the importance of these genes in the context of the studied regions of Kazakhstan. However, the data of E. Trampari *et al.* (2022) indicate that other genes also play an important role in biofilm formation and antibiotic resistance in other parts of the world.

CONCLUSIONS

The study revealed a significant prevalence of biofilm-forming Salmonella strains on poultry farms in Kazakhstan, Latvia, and Turkey. Samples were collected from a variety of sources, including faecal, tissue and water samples, allowing for a comprehensive analysis. It was found that 60% of the strains isolated from faeces, 26.7% from tissue and 13.3% from water showed a high degree of antibiotic resistance. The highest proportion of resistant strains was found in Kazakhstan, highlighting the need for greater control over the use of antibiotics in this region.

The majority of *Salmonella Enteritidis* and *Salmonella Typhimurium* strains were found to *have the* ability to form biofilms, which significantly complicates their treatment. The SE1 and SE2 subtypes of *Salmonella Enteritidis* and the ST1 subtype of *Salmonella Typhimurium* showed the highest tendency to biofilm formation, indicating their potential virulence and resistance to adverse conditions. These results highlight the importance of considering biofilm formation when developing infection control strategies. Antibiotic resistance analysis showed that 70% of Salmonella strains were resistant to at least one of the antibiotics tested, including ampicillin, tetracycline, and trimethoprim/sulfamethoxazole. Among these strains, the highest level of resistance was observed in *Salmonella Typhimurium,* where 62.5% of strains showed multidrug resistance. These data indicate the need to revise current practices of antibiotic use in veterinary medicine and develop new therapeutic approaches.

Correlation analysis showed a significant positive relationship between the level of biofilm formation and antibiotic resistance. This underlines the importance of developing methods aimed at destroying biofilms, which can increase the effectiveness of existing antibiotics. The introduction of regular monitoring of biofilm-forming strains and the use of specialized antibacterial agents aimed at destroying biofilms and preventing their formation is recommended. The results obtained are of significant practical importance for poultry farms, as they highlight the need to develop comprehensive infection control and prevention strategies. In particular, programmes for regular monitoring and control of antibiotic use should be implemented, and methods should be developed to reduce the ability of bacteria to form biofilms.

The limitations of this study include the use of only microbiological and molecular genetic methods without taking into account environmental factors and agricultural practices, which requires a further comprehensive approach to the study of the problem. The main areas for further research include a more detailed study of the genetic mechanisms responsible for biofilm formation and antibiotic resistance, as well as the development of new therapeutic approaches to overcome antibiotic resistance. It is also important to consider the impact of different environmental conditions and farming practices on biofilm formation and persistence.

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CONFLICT OF INTEREST

None.

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Вивчення антибіотикорезистентності штамів сальмонел, що утворюють біоплівку

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Анотація. Метою дослідження було вивчення поширеності та стійкості біоплівкоутворюючих штамів сальмонел на птахівничих фермах у Казахстані, Латвії та Туреччині. Під час дослідження з січня по грудень 2023 року було зібрано та проаналізовано зразки фекалій, тканин (печінка та кишківник) і води з поїлок. Виділення та ідентифікація штамів сальмонел проводилися з використанням стандартних мікробіологічних методів. Було виділено та ідентифіковано 150 штамів сальмонел, з яких 90 штамів було отримано з фекальних проб, 40 з тканинних проб і 20 з водних проб. Розподіл штамів за країнами показав, що в Казахстані, Латвії та Туреччині найбільшу кількість штамів було виділено з фекальних проб. Із 80 штамів *Salmonella Enteritidis* більша частина виявила здатність до утворення біоплівок, що визначалося методом crystal violet, причому підтипи SE1 і SE2 показали найбільшу схильність до біоплівкоутворення. Серед штамів *Salmonella Typhimurium* значна здатність до біоплівкоутворення була виявлена у підтипу ST1. Антибіотикорезистентність визначали за допомогою дискодифузійного методу. Штами, що утворюють біоплівки, показали вищу резистентність до антибіотиків, порівнюючи зі штамами, що не утворюють біоплівки. Зі 150 виділених штамів 105 показали резистентність до щонайменше одного з тестованих антибіотиків, причому найбільший рівень резистентності був серед штамів *Salmonella Typhimurium*. Кореляційний аналіз виявив значний позитивний зв'язок між рівнем біоплівкоутворення та резистентністю до антибіотиків. Отримані результати демонструють необхідність впровадження розробки нових методів контролю та профілактики інфекцій на птахівничих фермах, які б враховували особливості біоплівкоутворення та антибіотикорезистентності певних штамів

Ключові слова: фекальні проби; серотип; генетичний фактор; мультирезистентність; птахівництво

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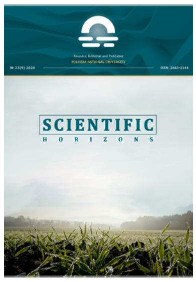

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Prospects for maize processing for the development of bioeconomy and decarbonisation in Ukraine

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Abstract. Under the terms of the European Green Deal, including the transition to a green economy, decarbonisation, and a sustainable model of inclusive growth, Ukraine has committed itself to achieving climate neutrality by 2060. The military challenges caused by Russia's full-scale invasion of Ukraine require an in-depth

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investigation and substantiation of mechanisms for developing promising areas of deep processing of domestic agricultural raw materials to ensure food security, domestic market development, and post-war economic recovery. The purpose of this study was to analyse and assess the potential for processing Ukrainian maize in the context of bioeconomy development, specifically to produce starch, bioplastics, and bioethanol. The study was conducted using a systematic approach with extrapolation methods, exponential smoothing, and confidence interval construction to assess the forecast. It was proved that Ukraine has all the opportunities to increase the production of a wider product line of deeply processed maize products. Realising the potential of maize processing as a biological and energy feedstock in the Ukrainian economy for post-war recovery depends on the creation of an innovative bioeconomy infrastructure, through strengthening strategic partnerships between agricultural producers, research institutions and public authorities, cluster development and export promotion. The practical value of this study lies in the developed recommendations for the implementation of maize processing opportunities for the development of the bioeconomy and acceleration of decarbonisation in Ukraine

Keywords: sustainable development; Green Deal; carbon footprint; deep processing of agricultural raw materials; added value; green energy

INTRODUCTION

One of today's global challenges that directly affects everyone's life is climate change, caused by the growth of greenhouse gas emissions from economic activity. Reduction of carbon dioxide emissions and mitigation of climate change can be achieved through decarbonisation and the development of the bioeconomy. Maize, as a versatile crop, can play a key role in both areas, as its processing into biofuels, bioplastics, animal feed, and biochemicals will contribute to greenhouse gas emissions reduction, sustainable economic development, and energy security. This demonstrates the relevance of researching sustainable practices, technological innovations, and balanced policies for deep processing of one of the most common and important crops – maize.

M.M. Miralles-Quirós *et al.* (2022) investigated the reasons for the increase in the greenhouse effect due to the accumulation of carbon dioxide, methane, nitrogen oxide, and fluorinated gases as a result of economic activity, which lead to global warming. Due to human activity, the temperature of Earth has risen by more than 1°C in 120 years. Global warming caused by human activity is increasing at a rate of 0.2°C per decade. If the situation is not remedied, in less than 50 years, humanity will reach a temperature increase of 2°C compared to pre-industrial levels. This rise in global temperatures is threatening life on Earth. J. Rosenboom *et al.* (2022) concluded that the bioeconomy, including biomass production and use, is essential for decarbonising the energy system and replacing fossil and energy-intensive materials through scenario planning for Austria with a reduction in greenhouse gas emissions of up to about 20% of the Kyoto Protocol baseline (United Nations Framework Convention on Climate Change, 1998). The scenarios were developed using an optimisation model that integrates the energy sector, land use, and biomass flows.

According to A.G. Rodríguez *et al.* (2019), the bioeconomy is based on biological resources and is a real alternative for decarbonising fossil fuels in the economy, which plays a fundamental role in the fight against climate change. Prospects for the use of bioeconomic technologies to achieve decarbonisation are being identified in many sectors of the economy. P. Kumar and M. Richardson (2017) compared the energy efficiency and environmental impact of different maize processing technologies for food and biofuel production and identified the economic and environmental impacts of using these resources. Based on the analysis and assessment of the impact of many factors, including energy, soil conditions, soil nutrients, and carbon storage, required for maize production and its conversion into biofuels, scientists have proven the prospects for developing maize production and processing as an energy crop for the future of renewable energy. J. Streimikis and T. Baležentis (2020) emphasise the significance of strong partnerships between international and national stakeholders, agricultural and research institutions, as well as civil society organisations, which play a key role in supporting the achievement of the Sustainable Development Goals.

The studies of Ukrainian researchers deserve special attention. Specifically, T. Kvasha and L. Musina (2015) analysed approaches to the development of a system of green growth indicators in Ukraine. I. Kravchenko *et al.* (2021) covered the theoretical aspects of greenhouse gas emissions taxation, summarised and systematised the experience of combining environmental taxation with the system of CO_2 emissions trading in European countries. O. Ryabchyn *et al.* (2021) define the concept of "greenness" as a synergy between reducing greenhouse gas emissions and caring for the environment, which is relevant for Ukraine. L.A. Horoshkova and E.V. Khlobistov (2020) identified the conditions for ensuring sustainable development in terms of emissions of harmful substances and waste generation, modelling the factors influencing these parameters and the overall environmental situation in Ukraine. In this context, the search for and implementation of effective technologies for deep processing of maize is relevant and promising for the development of the bioeconomy and accelerating Ukraine's decarbonisation within the framework of the European Green Deal and performance of its commitments. This involves not only setting targets and measures to reduce CO_2 emissions, but also devising and implementing a strategy for developing a resource efficient economy.

Considering the above, the purpose of this study was to substantiate the possibilities of deep processing of maize for the development of the bioeconomy and acceleration of decarbonisation in Ukraine as a key principle of the green transition and sustainable development.

MATERIALS AND METHODS

The focus of this study was to identify opportunities to increase production capacity in Ukraine for processing maize into starch, bioplastics, and bioethanol. To formulate a strategic vision and measures for the development of the green economy in Ukraine, it is advisable to build a forecast until 2032. Accordingly, a statistical sample was made for the last 11 years, i.e., from 2013 to 2023. The information base for the construction of these series was the UN Comtrade Database service (2024), State Statistics Service of Ukraine (2024), Annual National Inventory Report… (2023), Designing the Bioeconomy for Deep Decarbonisation (2021), ESOMAR Pro-Consulting (Starch market in Ukraine, 2021), Latifundist (Bioethanol, 2023), the Office of Technological Development Planning Unitika Ltd (Polylactic Acid, 2022), Fortune Business Insights (Food Additives & Ingredients, 2024). Since most international databases and services that provide data on exports of goods sometimes lack data on international trade in physical terms, it is advisable to use data on exports of goods in physical terms.

The Minitab statistical data processing tool was used to build the autocorrelation function and perform structural analysis of time series. This tool was used to analyse the time series according to various evaluation criteria. Trends were identified, an autocorrelation function was built, time series were decomposed, and the presence of seasonal fluctuations was determined.

The results of the time series analysis of exports made it possible to identify the most suitable methods for forecasting until 2030. Considering the above, it is advisable to use extrapolation methods and exponential smoothing and confidence interval construction to assess the forecast. Since the use of the exponential smoothing method is widely used in forecasting time series in the economy and has its advantages. To make a forecast based on the extrapolation method using exponential smoothing and building a confidence interval, it is advisable to use MS Excel, as the versions since 2016 have the necessary built-in capabilities and tools for making forecasts.

RESULTS AND DISCUSSION

The prospects for the development of the bioeconomy and decarbonisation are widely discussed in the public and scientific space, both abroad and in Ukraine. Areas of development of the bioeconomy, which, according to the GBS 2018 Communiqué, can be defined as the production, consumption, and protection of biological resources, based on knowledge, scientific achievements, technologies, and innovations to inform sustainable economic development, related to the deep processing of agricultural raw materials (Bioeconomy Policy Part III, 2018). However, the use of agricultural raw materials covers a wider range of industrial production, and their deep processing not only provides relevant effects in the areas of food security, resource efficiency and environmental protection, but can also act as one of the engines of post-war industrial recovery. The global nature and significance of concerted urgent action to counteract the growth of greenhouse gas emissions and its consequences is emphasised in the Sustainable Development Goals (United Nations, 2015). Thus, *Climate change 2022* (2022) substantiated the close connection of Sustainable Development Goal 13, "Combat climate change", with all 16 other goals of the 2030 Agenda for Sustainable Development.

T. Ronzon *et al.* (2020) have developed a methodology for monitoring the contribution of the bioeconomy to jobs and growth in the European Union and its Member States and have proven the strategic significance of the EU bioeconomy in guaranteeing a secure food supply, acting as a buffer for employment and providing a significant potential for the transition to an innovative resource – an efficient and competitive economy. Proceeding from the findings of the US Department of Energy's National Laboratories' 2021 studies, which proved that biotechnology is a vital tool for reducing greenhouse gas emissions, the areas of intervention to achieve decarbonisation goals are the transport sector, industry, and agriculture (Fig. 1).

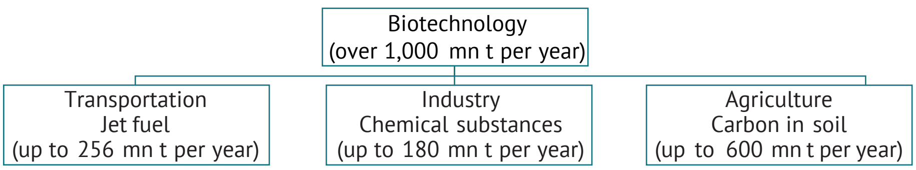

***Figure 1**. Potential greenhouse gas reduction effects of biotechnology in millions of metric tonnes per year*
***Source:** developed by the authors of this study based on Designing the Bioeconomy for Deep Decarbonisation (2021)*

Studies have shown that the introduction of biotechnology has a considerable impact on reducing greenhouse gases in the agricultural sector. These are biological systems to produce new products from sustainable biomass resources, including aviation fuel, high-performance fuel additives, recyclable bioplastics, enhanced soil microbial cultures to increase crop productivity, new hybrid biotechnologies and chemical synthesis processes, increased aboveground CO_2 capture and underground carbon storage, etc. (Designing the Bioeconomy, 2021). Biotechnological methods and processes in the energy sector can not only replace oil-based products, but also enable the development of new types of products. According to E. Trigo *et al.* (2023), the bioeconomy and the introduction of biotechnological innovations contribute to improved rural development, food production, and increased efficiency in the production of crops, livestock, biofuels, bioplastics, and bioenergy. This allows food systems to transform to become more sustainable and equitable, providing healthy, nutritious food while creating livelihoods and reducing negative impacts. This is the priority for Ukraine's economic recovery. Deep processing of maize allows producing about 18 types of high value-added products.

The potential of using maize as an energy feedstock is one of the most promising areas of bioeconomy and decarbonisation. This is also emphasised by Ukrainian scientists G. Kaletnik *et al.* (2021), who substantiated the technology of growing maize and obtaining alternative fuels, which will have a positive impact on the energy supply of local consumers. Furthermore, C.R. Parra *et al.* (2023) have proved that increasing the share of alternative sustainable energy sources such as biomass is crucial to meet both peak and baseload electricity demand in future scenarios. The dynamics of the key indicators characterising the production and export potential of maize as an energy feedstock and greenhouse gas emissions is presented in Table 1.

Table 1. *Dynamics of production, exports, and greenhouse gas emissions in Ukrainian agriculture in 2013-2023*

Indicator	Years										
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
GDP in factual prices, UAH bn	1,465.20	1,586.92	1,988.54	2,385.37	2,981.23	3,560.30	3,977.20	4,222.03	5,450.85	5,239.11	6,537.83
Volume of agriculture, forestry, and fisheries, UAH bn	128.74	161.15	239.81	279.70	303.42	361.00	356.56	393.08	593.37	449.15	484.15
Share of agriculture, forestry, and fisheries in GDP, %	8.79	10.15	12.06	11.73	10.18	10.14	8.97	9.31	10.89	8.57	7.41
Total exports, USD bn	63.30	53.90	38.10	36.40	43.30	47.30	50.10	49.20	68.10	44.10	36.20
Agroindustrial exports, USD bn	17.04	16.67	14.60	15.30	14.90	18.60	22.10	22.20	27.70	20.90	22.01
Maize exports, bn USD	3.83	3.35	3.00	2.65	2.99	3.51	5.22	4.89	5.85	5.99	5.00
Share of maize in agricultural exports, %	22.49	20.10	20.56	17.34	20.06	18.85	23.61	22.00	21.13	28.67	22.70
Greenhouse gas emissions, total mn t – equivalent (CO_2)	409.00	362.60	319.20	337.60	323.30	339.80	334.10	318.00	330.40	–	–
Greenhouse gas emissions in agriculture, total mn t - equivalent (CO_2)	41.60	41.40	39.40	42.00	41.00	44.40	44.80	41.70	47.00	–	–
Share of greenhouse gas emissions from agriculture in total emissions, %	10.17	11.42	12.34	12.44	12.68	13.07	13.41	13.11	14.23	–	–

Source: *developed by the authors of this study based on research by UN Comtrade Database (2024), State Statistics Service of Ukraine (2024), Annual National Inventory Report, (2023)*

These data suggest that despite the gradual decline in the share of agricultural output from 8.79% of GDP in 2013 to 7.41% in 2023, agri-food exports continue to grow, and their share in total exports will stay significant at 60.8% in 2023. Maize exports account for a significant share of total agri-food exports and grew from 22.49% in 2013 to 22.7% in 2023, amounting to USD 5.0 bn in value in 2023. This indicates an increase in raw material exports instead of highly processed products. At the same time, greenhouse gas emissions in agriculture increased during the study period and reached 14.23% of total emissions in 2021. This confirms the significance and necessity of developing the types of deep processing of agricultural raw materials that reduce the carbon footprint.

According to S.R. Padhan *et al.* (2023), maize-based biofuels are promising because they can reduce greenhouse gas emissions, biodegradability, and clean combustion, which increases energy security. However, increasing the production of maize-based biofuels requires breeding strategies such as crossbreeding selected varieties to increase biomass and starch content. Better agronomic practices and extension strategies are also needed to increase yields and promote adaptation among farmers. Using maize as a feedstock for biofuel production can stimulate the agricultural sector, create jobs in agriculture, food processing, and transport, and reduce dependence on foreign oil while preserving foreign exchange reserves.

One of the most promising areas of deep processing is maize starch, which is the basis for the production of packaging materials that are easily destroyed during recycling (Starch modifications, 2023). Starch is widely used in the food industry as a thickener or stabiliser for bread, soups, puddings, cakes, soy, meat products and sauces, vermicelli, ice cream biscuits, instant noodles, sago, chocolates, etc. Furthermore, the functional advantages of starch considerably expand the range of applications in various industries (Fig. 2).

In 2023, the global maize starch market reached 86.4 mn t and, according to IMARC Group, will reach 106.3 mn t by 2032, or an increase of 2.5% (IMARC Group, 2024). In 2032, its size will increase to USD 127.07 bn. (Fig. 3).

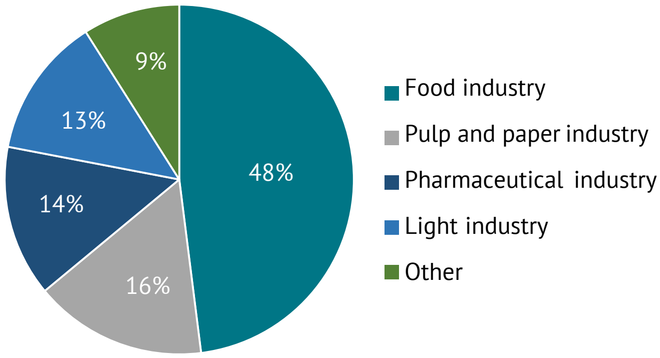

***Figure 2**. Areas of application for maize starch, %*
***Source:** developed by the authors of this study based on research by Pro-consulting Insights (Starch market in Ukraine, 2021)*

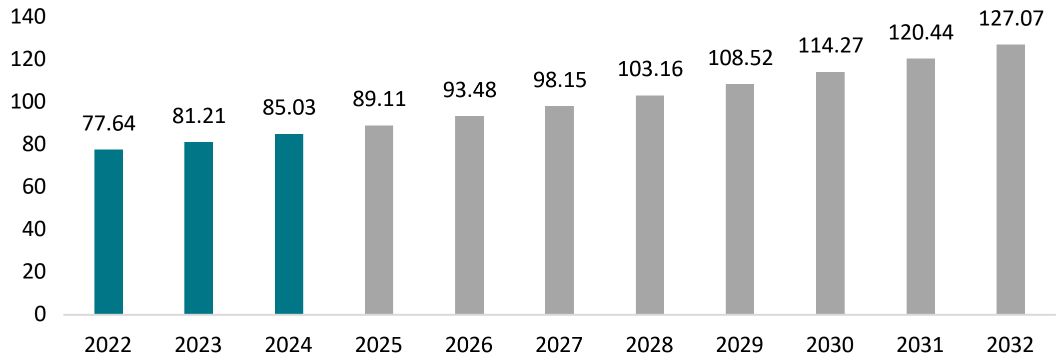

***Figure 3**. Global maize starch market development dynamics in 2022-2024 and forecast to 2032, USD bn*
***Source:** developed by the authors of this study based on research by Fortune Business Insights (Food Additives & Ingredients, 2024)*

This is also confirmed by the findings of P. Adewale *et al.* (2023), who considered the prospects for the production of starch-based products, namely the growth of non-food production from maize starch, which will provide access to new markets, increase profits, etc., within the framework of the Sustainable Development Goals. The factors contributing to this growth are as follows:

- urbanisation, which leads to busier lifestyles and greater reliance on packaged and processed food;
- demand for culinary semi-finished and processed products, where starch is a key ingredient for texture, stability, and other functional properties;
- development of pharmaceuticals, production of bioethanol and bioplastics;
- emergence of new technological developments, including the use of starch as a potential ingredient in alternative protein products and as a raw material for renewable and biodegradable packaging materials;

- improvement of the functional properties of starch, including texture, thermal stability, viscosity, and solubility, to improve product quality;
- population growth and rising incomes, particularly in the Asia-Pacific region (China, India), leading to increased demand for a variety of consumer products, including processed foods, pharmaceuticals, and industrial products based on starch as an ingredient, with a projected average annual growth of more than 5% until 2028.

Ukraine has all the prerequisites for developing maize starch processing and entering the global market: high bioproductive potential of land resources and favourable climatic conditions. The largest producers are Interstarch Ukraine, Vimal Ukraine, the Yuvileinyi modified fats and starches plant, Kremnianskyi Starch Plant, and Dnipro Starch Processing Plant, with over 50 companies across the country. Ukraine has considerable export potential for maize starch, as presented in Table 2.

***Table 2**. Exports and imports of maize starch in 2013-2023*

Seq. No.	Year	Export		Import	
		Volume, mn USD	Volume, thsd t	Volume, mn USD	Volume, thsd t
1	2013	10.70	19.44	1.92	3.28
2	2014	8.71	20.81	1.45	3.31
3	2015	9.72	28.11	0.78	1.61
4	2016	9.56	31.44	1.36	1.99
5	2017	18.59	61.16	4.52	10.68
6	2018	20.61	60.63	4.12	9.95
7	2019	28.58	82.70	1.26	1.17
8	2020	28.06	74.43	1.52	1.03
9	2021	38.37	78.74	1.47	0.88
10	2022	52.17	53.44	0.80	0.52
11	2023	30.78	33.94	3.71	5.17

***Source:** developed by the authors of this study based on research by UN Comtrade Database (2024) and State Statistics Service of Ukraine (2024)*

These data suggest an almost 3-fold increase in maize starch exports from 2013 to 2023 in value terms. At the same time, imports increased from USD 1.92 mn in 2013 to USD 3.71 mn in 2023. For comparison, total exports of maize, which could become a raw material for starch and other higher value-added products, amounted to USD 4,966.26 mn in value terms in 2023, which is 161.33 times more than exports of maize starch of USD 30.78 mn.

The starch market in Ukraine is characterised by a raw material orientation of agri-food exports, low levels of fixed assets, and insufficient number of employees. During the COVID-19 pandemic, the internal starch market was characterised by a decline in demand for sausage and meat products that use starch, which led to a contraction in the market. This opened opportunities for increased imports of foreign starch. At the same time, the decline in internal demand because of the war has led to the accumulation of starch stocks in producers' warehouses and the need to reorient to foreign markets (starch stocks at the end of 2022 amounted to 50 thsd t, while internal consumption was 12 thsd t). Based on the author's calculations, if Ukraine establishes corn starch production, corn starch exports will have a positive annual growth rate of 7.39% on average by 2030. In 2030, the projected export volumes of the product under study will increase to USD 73.2 mn on average, with a possible deviation ranging from USD 55.0 mn to USD 91.3 mn (Fig. 4).

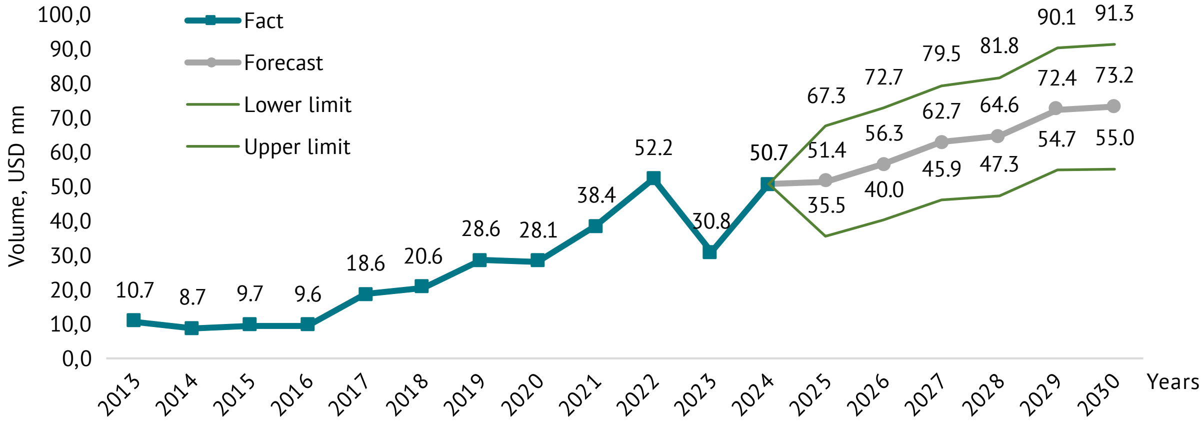

Figure 4. *Dynamics of maize starch exports in 2022-2024 and forecast for 2025-2030, USD mn*
Source: *calculated by the authors of this study based on data from the State Statistics Service of Ukraine (2024)*

Another promising area of maize processing, especially relevant in the context of the green transition and achieving sustainable development goals, is the production of bioplastics based on polylactic acid (PLA). According to A.P. Thomas *et al*. (2023), bioplastics play a significant role in the bioeconomy as they are easily recyclable and can mitigate environmental impacts by replacing conventional plastics. This trend is in line with global efforts to reduce plastic waste and promote sustainability. Plastics and industrial chemicals can be created from deconstructed biomass, which contains a series of components not found in fossil resources. G. Fredi and A. Dorigato (2021) point out that biodegradable bioplastics have alternative waste disposal pathways, limiting the amount of plastic waste that enters the environment, while biobased bioplastics can substantially reduce the carbon footprint at the resource extraction stage. Maize-based bioplastics have advantages in terms of performance, recyclability, while reducing energy and resource consumption, namely:

- energy consumption is 65% lower than that of conventional oil-based plastics;
- maize-based biopolymers could reduce greenhouse gas emissions across the industry by 25%, or 16 mn t of CO_2e/year;
- biodegradability – bioplastics decompose quickly and can break down in 45-90 days;
- no toxic fumes during the combustion of bioplastics;
- lower water consumption during bioplastics recycling;
- approaching international environmental standards.

One of the advantages of bioplastics is that they can be composted until they are fully decomposed within three months. The composting equipment ensures that this material decomposes at temperatures ranging from +55°C to +70°C and at a special humidity level. Furthermore, the processing of bioplastics produces considerably less carbon dioxide and other greenhouse gas emissions than the combustion of polymers such as PS (polystyrene), PET (polyethylene terephthalate), PP (polypropylene), and PE (polyethylene), which leaves a smaller carbon footprint (Fig. 5).

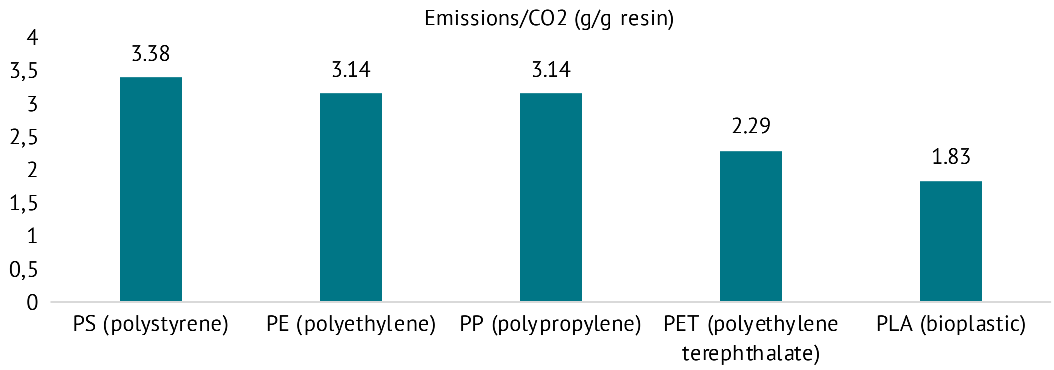

Figure 5. *Amount of CO_2 emissions into the atmosphere during combustion, g/g of resin*
Source: *compiled by the authors of this study based on Polyactic Acid studies (2022)*

The global bioplastics and biopolymers market is expected to reach USD 93.1 bn by 2032, at an annual average growth rate of 11.3% during the forecast period from 2025 to 2033. At the same time, the growth of maize-to-bioplastics production capacity also has potential risks. Specifically, G. Atiwesh *et al.* (2023) found that the production of bioplastics from plants such as maize requires the conversion of land for plastic production instead of meeting food needs, as almost 25% of agricultural land used for grain production is used for biofuels and bioplastics. This could lead to a considerable increase in food prices, which would have negatively affected the economically disadvantaged groups.

The bioplastics market in Ukraine is growing and new players are entering the market. This is primarily due to the regulatory framework in the context of compliance with the requirements of the European Green Deal. On 1 June 2021, the Verkhovna Rada of Ukraine adopted Law of Ukraine No. 1489-IX (2021). It is aimed at reducing the consumption of plastic bags in Ukraine. It also makes provision for restrictions on the distribution of plastic bags to improve the environment and reduce the anthropogenic impact on the environment. The Law does not apply to biodegradable plastic bags, but prohibits the distribution of ultra-thin, thin oxo-degradable plastic bags. Thanks to the Law, demand for biodegradable bags almost doubled in 2022, and consumption of plastic bags decreased by 40-90% depending on their type.

An innovative technology to produce bioplastics from maize has been developed in Ukraine by BIOC, a start-up that meets international standards for product quality and safety. BIOC bioplastics are triple copolymerised and are fully biodegradable. In its structure, modified maize starch makes up 50 to 75% (Innovative technology, 2024). Ukraine, which has a considerable potential for bioplastics production, continues to import it, as presented in Table 3.

Table 3. *Exports and imports of bioplastics in 2013-2023*

Seq. No.	Year	Export		Import	
		Volume, mn USD	Volume, thsd t	Volume, mn USD	Volume, thsd t
1	2013	0.097	0.016	27.0	6.6
2	2014	0.183	0.033	24.6	6.4
3	2015	0.171	0.050	19.9	6.1
4	2016	0.143	0.020	21.5	–
5	2017	0.087	0.030	26.2	7.5
6	2018	0.130	0.028	28.5	7.8
7	2019	0.138	0.021	27.5	–
8	2020	0.154	0.023	25.9	–
9	2021	0.149	0.028	29.6	–
10	2022	0.391	0.067	19.5	4.4
11	2023	0.043	0.012	29.1	7.3

Source: *developed by the authors of this study based on research by UN Comtrade Database (2024) and State Statistics Service of Ukraine (2024)*

These data show that during 2013-2023, the volume of bioplastics imports, except for 2014, 2015, 2020, and 2022, tended to grow. Export volumes are insignificant and fluctuated during the study period from USD 0.097 mn in 2013 to USD 0.043 mn in 2023. Based on forecasts, it was determined that bioplastics exports will grow until 2030 but will not reach the level of 2022. At the same time, considering the increase in the production of bioplastics from maize in Ukraine, the projected exports of the product under study in 2030 could reach a maximum level of USD 0.47 mn, but will average USD 0.29 mn in 2030 (Fig. 6).

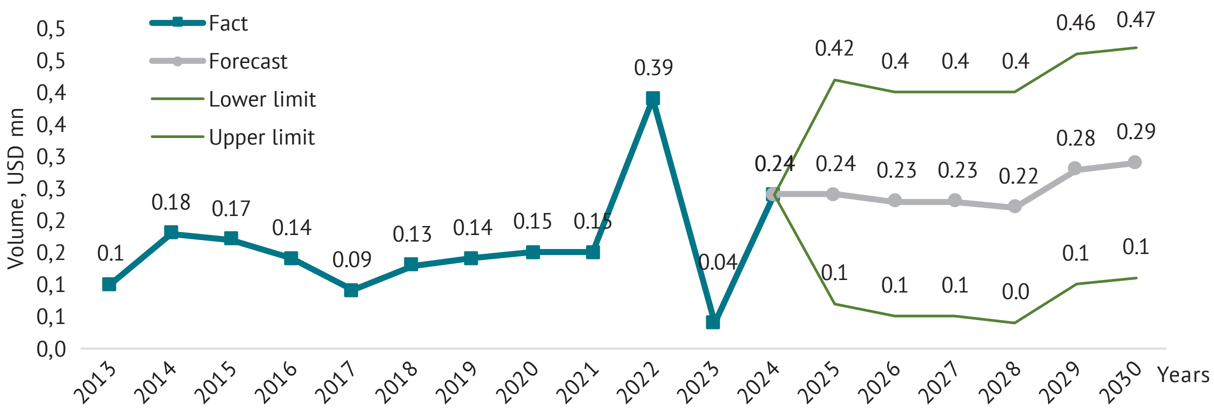

Figure 6*. Forecast of bioplastics exports by 2030, USD mn*
Source: *calculated by the authors of this study based on data from the State Statistics Service of Ukraine (2024)*

Among its many uses, maize can be used as a feedstock for alternative energy sources, including bioethanol. C. Bataille *et al.* (2018) concluded that the reduction of energy-intensive industrial greenhouse gas emissions in line with the commitments of the Paris Agreement (United Nations Framework Convention on Climate Change, 2015) can be achieved through energy efficiency measures using renewable energy sources, which will be cost-effective.

Demand for bioethanol is growing globally from various feedstocks, including barley, rye, wheat, and maize. To meet this demand, it is necessary to increase grain production by 10-15 mn t annually. In 2022, Ukraine's bioethanol production capacity was estimated at around 381 thsd t per year. Therewith, almost three quarters of them (282,000 t) are located over 200 km away from the combat zone, which makes it possible to continue its production. According to a survey conducted by the Ukrainian Association of Bioethanol Producers, production volumes in 2019 were 80 thsd t, in 2020 – 73 thsd t, and in 2021 – 77 thsd t (Bioethanol, 2023). In 2023, the volume of bioethanol exports amounted to USD 3.56 mn (Table 4).

Table 4*. Exports and imports of bioethanol in 2013-2023*

Seq. No.	Year	Export		Import	
		Volume, mn USD	Volume, thsd t	Volume, mn USD	Volume, thsd t
1	2013	0	–	0.006425	0.000295
2	2014	4.96	5.62	4.573133	5.616666
3	2015	0.0007	0.0013	0.001171	0.000842
4	2016	0	–	0.003727	0.000511
5	2017	0.02	0.02	0.000145	0.000010
6	2018	0.00	–	0.003728	0.001734
7	2019	0.05	0.06	0.006478	0.001584
8	2020	5.44	8.11	0.000854	–
9	2021	0.32	0.40	0.100431	0.081683
10	2022	4.70	5.41	0.001448	0.000158
11	2023	3.56	5.10	0.002482	0.000125

Source: *developed by the authors of this study based on research by the UN Comtrade Database (2024) and the State Statistics Service of Ukraine (2024)*

The bioethanol produced in Ukraine is mainly used for domestic consumption, which indicates the need to increase the volume of maize processing in the internal market. Maize has the highest product yields, for instance, 100 t of maize produces 46.7 m^3 of bioethanol, 36.5 t of CO_2 and 90 t of DDGS. In 2022, Ukraine harvested 27 mln t of maize, and in 2023 – approximately 30.1 mln t. At the same time, the share of processed maize for bioethanol did not exceed 2.5%. There are many companies operating in the Ukrainian bioethanol market, including the largest ones such as Naftogaz Bioenergy, the Renewable Energy Agency, Biomass Science and Technology Centre, MHP Eco Energy, GTS Operator of Ukraine LLC, GALS AGRO LLC, Kernel, Vitangro Group, and many others.

The factors that determine the prospects for using maize as a feedstock for future biofuels in Ukraine are as follows:

- both maize kernels and maize stalks are used for bioethanol production;
- due to its long shelf life and the ability to be processed throughout the year, maize is an alternative source of energy for industrial production;
- considerably higher than in other crops (soybean and sunflower yields of 3 t/ha, maize yields of 10 t/ha of grain and 10 t/ha of stalks) allows for the production of 3.1 t/ha of protein feed and enables the production of bioethanol (3.5 t/ha) (Ukrainian technology company, 2024);
- Ukraine's compliance with the requirements of the European Green Deal. Back in 2021, the Verkhovna Rada of Ukraine adopted in the first reading the Law of Ukraine No. 3356-d (2021) on the mandatory use of liquid biofuels (biocomponents) in the transport sector. Fuel producers in the EU specify a 5% or 10% bioethanol content in fuel, which affects pricing, and this stimulates internal production of bioethanol in the European Union. In Ukraine, it is planned to increase the share of bioethanol to 5% in transport fuel. This will bring the quality of Ukrainian fuel closer to European standards and will have a positive environmental effect and contribute to the sustainable development of the national agricultural sector (Draft Law of Ukraine, 2024).

Under martial law, the role of alternative energy sources, specifically bioethanol, in the context of ensuring national energy security has significantly increased. Apart from the transport sector, companies in related industries, such as chemicals and mining, have begun to consume bioethanol more actively. Based on forecasts, it was determined that bioethanol exports will grow slowly until 2030, and will not only reach the level of 2020 exports but also exceed it. Considering the growth of maize-based bioethanol production in Ukraine, the projected export volumes of the product under study in 2030 may reach a maximum level of USD 13.69 mn, and on average will amount to USD 9.3 mn (Fig. 7).

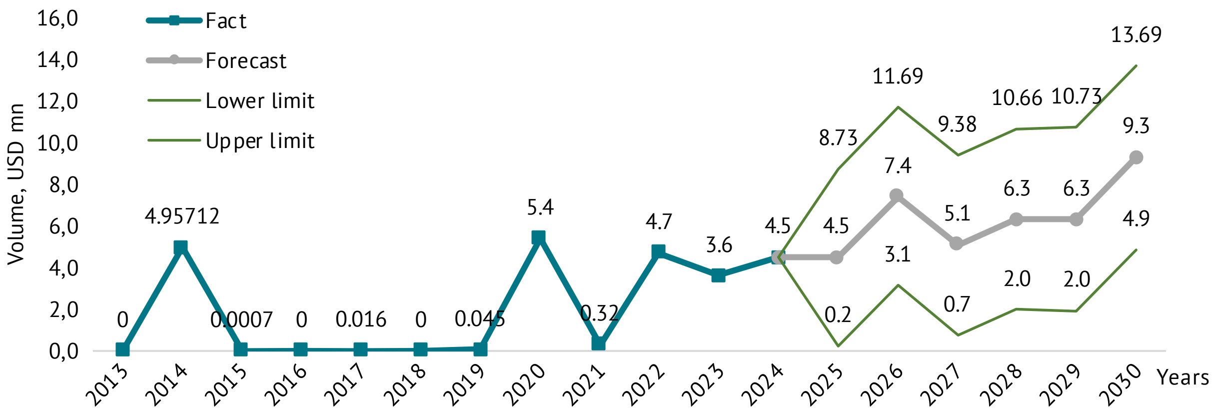

***Figure 7**. Forecast of bioethanol exports by 2030, USD mln*

***Source:** calculated by the authors of this study based on data from the State Statistics Service of Ukraine (2024)*

In 2024, Ukraine will gradually introduce the practice of adding bioethanol to fuel, but the vast majority of it is exported to the EU. G. Seber *et al.* (2022) substantiated the benefits of using sustainable aviation fuels from vegetable oils as one of the most promising short- and medium-term options for mitigating greenhouse gas emissions from aviation. A. Arias *et al.* (2024) focused on current trends in the production of biofuels for the marine and aviation sectors, considering the principal goals set, existing rules and directives in regulating these activities, analysing the type of biofuels and technologies used for their production. This once again confirms the importance of developing national bioethanol production. The inclusion of this area in the strategic directions of Ukraine's industrial recovery will help to increase national bioethanol production.

R. Hechelmann *et al.* (2023) covered the prospects of using biomethane to reduce greenhouse gas emissions for eight German manufacturing companies in various industries by conducting a greenhouse gas emissions inventory and identifying operational measures to reduce emissions, considering GAP and cost-effectiveness, which became the basis for developing a decarbonisation roadmap. The present study does not present all the possibilities of in-depth processing of maize as a promising energy agricultural raw material. Further research could be aimed at substantiating new maize processing technologies and bringing them into line with European technical regulations, which would help reduce greenhouse gas emissions in the context of decarbonisation.

CONCLUSIONS

Ukraine has not yet fully exploited its bioeconomic potential in maize processing, focusing mainly on commodity exports and fossil fuels. A considerable portion of value added, profits, foreign exchange earnings, and job opportunities stay abroad. One of the most promising areas of deep processing is the production of maize starch. Based on the author's calculations, if Ukraine establishes corn starch production, corn starch exports will have a positive annual growth rate of 7.39% on average by 2030. In 2030, the projected export volumes of the product under study will increase to USD 73.2 mn on average, with a possible deviation ranging from USD 55.0 mn to USD 91.3 mn.

Maize-based biopolymers can reduce greenhouse gas emissions by 25%, or 16 mn t of CO_2e/year. Based on forecasts, it was determined that bioplastics exports will grow until 2030 but will not reach the level of 2022. At the same time, considering the increase in the production of bioplastics from maize in Ukraine, the projected exports of the product under study in 2030 may reach a maximum level of USD 0.47 mn, but will average USD 0.29 mn in 2030. Based on forecasts, it was determined that bioethanol exports will grow slowly until 2030 and will not only reach the level of 2020 exports but also exceed it. Considering the growth of maize-based bioethanol production in Ukraine, the projected export volumes of the product under study in 2030 may reach a maximum level of USD 13.69 mn and will average USD 9.3 mn.

Prospects for further research on this topic include scientific support for the development of other areas of deep processing of maize as a biological and energy crop, including the production of gluten, amino acids, paints, varnishes, biogas, biodiesel, etc., the development of which is important for achieving the Sustainable Development Goals, namely combating climate change, environmental pollution, depletion of fossil mineral resources, and the spread of renewable energy sources, transition to rational production models, and ensuring food security.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Перспективи переробки кукурудзи для розвитку біоекономіки та декарбонізації в Україні

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Анотація. Відповідно до умов Європейського зеленого курсу, зокрема щодо переходу до зеленої економіки, декарбонізації та сталої моделі інклюзивного зростання, Україна взяла на себе зобов'язання досягнути кліматичного нейтралітету до 2060 року. Воєнні виклики, зумовлені повномасштабним вторгненням рф в Україну, вимагають поглибленого вивчення та обґрунтування механізмів розвитку перспективних напрямів глибокої переробки власної сільськогосподарської сировини для забезпечення продовольчої безпеки, розвитку внутрішнього ринку та повоєнного відновлення економіки країни. Метою дослідження був аналіз та оцінка можливостей переробки української кукурудзи в контексті розвитку біоекономіки, зокрема для виробництва таких продуктів як крохмалю, біопластику та біоетанолу. Дослідження здійснювалися за системним підходом із використанням методів екстраполяції та використання експоненціального згладжування і побудови довірчого інтервалу для оцінки прогнозу. Доведено, що в Україні є всі можливості для зростання обсягів виробництва більшої продуктової лінійки продуктів глибокої переробки кукурудзи. Реалізація потенціалу переробки кукурудзи як біологічної та енергетичної сировини в українській економіці для повоєнного відновлення залежить від створення інноваційної інфраструктури в частині біоекономіки, за рахунок зміцнення стратегічного партнерства між сільськогосподарськими виробниками, науковими установами та органами державної влади, кластерного розвитку та стимулювання експортної діяльності. Практичною цінністю роботи є розроблені рекомендації щодо реалізації можливостей переробки кукурудзи для розвитку біоекономіки та прискорення декарбонізації в Україні

Ключові слова: сталий розвиток; Зелена угода; вуглецевий слід; глибока переробка сільськогосподарської сировини; додана вартість; зелена енергетика

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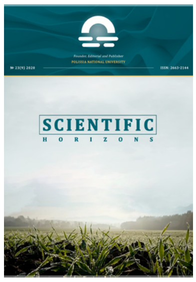

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Sinapis alba L. as an important green manure and fodder crop in the Carpathian region of Ukraine

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Abstract. White mustard is an important green manure and fodder crop in the Carpathian region. The purpose of this study was to determine the indicators of fodder productivity and chemical composition of fodder of white mustard varieties recommended for cultivation in the studied soil and climatic zone. The methodological framework of this study was formed by general scientific and special

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research methods. The findings presented in the study for 2021-2023 highlight the dynamics of accumulation of vegetative mass and dry matter of white mustard in different major growth stages and development phases (BBCH) and the chemical composition of the feed. Studies have shown that the climate changes observed in recent years with increased temperature and sufficient rainfall meet the biological requirements of crop cultivation, while the created high-performance varieties meet the requirements of agricultural production of both seeds and green mass. It was found that per 1 ha the varieties Ariadna and Bila Pryntsesa leave about 9.9-10.1 t/ha of root residues in the soil and form a high yield of green mass (37.1-37.8 t/ha), which can be used for green fertiliser in the sixth stage of growth (flowering) of the BBCH 65 phase (full flowering: 50% of flowers on the main raceme are open, old petals have fallen off). Although the chemical composition of the biomass is somewhat inferior to conventional fodder crops, the crop under study can provide a balanced fodder in combination with high-protein crops. In the main sixth stage (flowering), the developmental phase BBCH 65, the value of the varieties was 4.081-4.158 t/ha of feed units and 5.194-5.292 t/ha of digestible protein. The findings of this study can be used by agricultural enterprises and farms for both green manure and fodder, which will increase soil fertility and improve animal nutrition

Keywords: white mustard; variety; green mass; fodder unit; digestible protein; quality

INTRODUCTION

The search for alternative types of green manure crops that can compete with conventional ones has led to an increase in the share of white mustard in the structure of sown areas. The solution to the problem of green manuring crops is closely related to the biological characteristics of the varieties introduced into agricultural production and their ability to form a large vegetative mass in the soil and climatic conditions of cultivation. According to S.S. Dhaliwal *et al.* (2021) and T.V. Melnichuk *et al.* (2023), the production volumes of niche oilseeds can be achieved by increasing the yield and sowing qualities of the grown seeds.

The phytomeliorative properties of white mustard are high, as it leaves about 5.5-6.0 t/ha of air-dry mass of root and stubble residues. The value of the crop is also in the fact that, with the decrease in soil organic matter content observed in recent years by almost 4-5 times, it can replenish it with labile forms of nutrients. The deeply penetrating roots of the crop (up to 2.5 m) convert hard-to-reach phosphates into easily assimilated forms of phosphorus. It builds up a large biomass in a short time and before flowering, which occurs in 60-75 days depending on the variety, forms a good cover layer that suppresses weeds, prevents erosion processes, promotes the active action of microorganisms, reduces the damage to subsequent crops by diseases and the spread of pests (Tsitsyura *et al.*, 2022).

Due to the essential oil and other biologically active compounds secreted by the plant, mustard effectively inhibits root rot, scab, phytophthora rot and fusariosis, blackleg and rhizoctonia pathogens. A.V. Melnyk *et al.* (2019a; 2019b) argue that among all types of mustard, white mustard is the most versatile for growing in the face of climate change. This crop should be introduced into the crop rotation to reduce the risk compared to conventional crops, which in a brief time allows enriching the soil with many easily accessible nutrients and increasing its overall soil fertility. The green mass of mustard in the amount of 15.0-20.0 t/ha ploughed into the soil is equivalent in terms of nutrients to the use of 20 t/ha of manure.

Mustard has a great phytosanitary role as a green manure crop in neutralising soil fatigue, incompatibility in the crop rotation system to increase the gap for placement in a monoculture. According to L.V. Hubenko and O.Ya. Liubchych (2020), when ploughed into the soil, green manure biomass decomposes easily and evenly, filling it with nutrients. The use of green manure crops, specifically white mustard as a green manure, provides a sufficient amount of organic matter and enriches available forms of phosphorus and nitrogen, especially soils poor in natural fertility, increases the water resistance of structural particles, increases capillary humidity, resulting in improved water regime and reduced acidity (Sivak & Kostyukevich, 2021).

White mustard can be grown both pure and mixed with other crops for green fodder. This crop does not require high costs for post-harvest sowing, due to the lower seeding rate and shallow and simplified cultivation, according to P. Jia *et al.* (2021a; 2021b), and S. Butenko *et al.* (2022). According to I.J. Irin *et al.* (2020), mustard produces high yields of green mass – 25-30 t/ha, which corresponds to 20 t/ha of organic fertiliser. With the application of 1 t of dry weight, the soil is replenished with 15-25 kg of nitrogen, 5 kg of phosphorus and up to 80 kg of potassium. And 100 kg of white mustard green mass contains 12 feed units and about 1.5 kg of digestible protein (Butenko & PeiPei, 2022).

The technology of white mustard cultivation will be of interest to many countries around the world. Based on the study conducted by A. Sarkar *et al.* (2021), chemical fertiliser doses (RDF) and foliar application of DAP (2.0% concentration), or urea (2%), or sulphur (0.5%) were found to improve plant growth and development and yield of hybrid mustard and improve nutrient status of the Ganges alluvial soil of West Bengal.

Considering the somewhat low degree of systematic scientific research on white mustard cultivation, which is controversial and mostly focused on the seed productivity of the crop by individual elements of technology, publications on fodder productivity are few and far between. The purpose of this study was to determine the dynamics of green mass growth by growth stage and plant development phase (BBCH) and nutritional value of fodder of Ariadna and Bila Pryntsesa varieties recommended for cultivation in the studied soil and climatic zone.

MATERIALS AND METHODS

The study was conducted in 2021-2023 at the Department of Seed Production and Seed Science of the Institute of Agriculture of the Carpathian Region of the National Academy of Agrarian Sciences (49°47′07″ N, 23°52′07″ E, 314 m above sea level). The grey forest, surface-ashy, light loamy soil of the experimental plots was characterised by the weighted average agrochemical parameters: low humus content (according to Tyurin) – 2.3% and the amount of absorbed bases – 13.7 mg-eq per 100 g of soil, soil pH – 5.4 – slightly acidic. The soil has a low content of easily hydrolysed nitrogen (according to Kornfield) – 89.6 mg/kg of soil and exchangeable potassium (according to Kirsanov) – 68.0 mg/kg of soil, and an average content of mobile phosphorus – 69.5 mg/kg of soil. In 2021, the hydrothermal coefficient (HTC) was excessive at 1.71, and optimal in 2022 at 1.31 and in 2023 at 1.58 (Fig. 1).

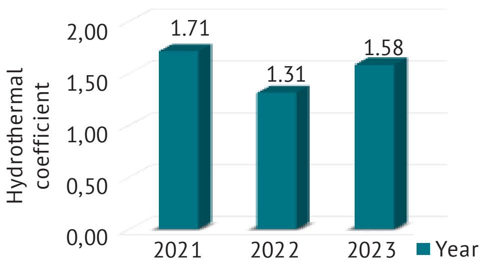

***Figure 1**. Humidity level (2021-2023)*
***Source:** compiled by the authors*

The agricultural technique of white mustard cultivation was generally accepted for the growing area and included: the predecessor – maize, sowing date – the third decade of April, conventional row sowing method (15.0 cm) with a seeding rate of 1.5 million germinating seeds/ha and a planting depth of 2-4 cm. The pesticides used were Modesto, 48% FC (insecticidal and fungicidal action, 12.5 l/t), roundup, 48% AS (2-3 weeks before ploughing), butyzan, 40% SC (1.75-2.50 l/ha) and calypso, 48% SC (0.25-0.40 l/ha).

The object of research included varieties: Ariadna (Carpathian State Agricultural Research Station of the Institute of Agriculture of the Carpathian Region of the National Academy of Agrarian Sciences of Ukraine) and Bila Pryntsesa (National Research Centre "Institute of Agriculture of the National Academy of Agrarian Sciences of Ukraine"). The study was conducted using the following methods: methodology for the examination of white mustard (*Sinapis alba* L.) varieties for distinctiveness, uniformity and stability (Methodology..., 2023); green mass yield was determined by the method of accounting plots; chemical composition – using the SupNir 2700 infrared analyser. Quality indicators – by infrared spectroscopy; statistical analysis of the results – according to the method of V.O. Ushkarenko *et al*. The results were calculated using *Microsoft Excel*. The study followed the standards of the Convention on Biological Diversity (1992) and the Convention on Trade in Endangered Species of Wild Fauna and Flora (1979).

RESULTS AND DISCUSSION

The intensive development of the vegetative mass of white mustard during the years of research was ensured by a prominent level of mineral nutrition $N_{110}P_{90}K_{100}$ and a sufficient amount of precipitation during the germination-flowering period (HTC) (Fig. 2).

***Figure 2**. Sowing of white mustard on the Institute's experimental plots (2023)*
***Note:** a) BBCH 65, b) BBCH 75*

According to the dynamics of green mass accumulation in the main growth stage 1 (leaf development), phase BBCH 18 (8 leaves unfolded), the average for the years was 31.1 t/ha for Ariadna and 31.2 t/ha for Bila Pryntsesa. By stage 5 (inflorescence), phase BBCH 50 (flower buds covered with leaves), the growth by varieties was 3.7 t/ha and 4.5 t/ha, respectively, while in the 6th stage of growth (flowering), phase BBCH 65 (full flowering: 50% of flowers on the main raceme are open, old petals have fallen off) – 6.0 t/ha and 6.6 t/ha (Table 1).

The high yields of green mass and dry matter in 2021 and 2023 were caused by moisture supply, with excessive HTC of 1.71 and 1.58, which had a positive impact on plant growth intensity from the early stages of organogenesis. At the 6th stage of growth (flowering), BBCH 65, the average yield of Ariadna was 37.1 t/ha, Bila Pryntsesa – 37.8 t/ha, and no significant differences between varieties were observed ($NIR_{0.05}$ = 1.0-1.5 t/ha).

***Table 1**. Dynamics of green mass accumulation of white mustard varieties (2021-2023), t/ha*

Growth stage, developmental phase (BBCH)	Variety, year									
	Ariadna			mean	± to control	Bila Pryntsesa			mean	± to control
	2021	2022	2023			2021	2022	2023		
1, BBCH 18	32.5	29.3	31.6	31.1	–	32.7	30.8	32.4	32.0	–
5, BBCH 50	36.7	32.6	35.1	34.8	3.7	37.2	34.9	35.1	35.7	3.7
6, BBCH 65	38.2	35.8	37.4	37.1	6.0	39.5	36.2	37.6	37.8	5.8
$LSD_{0.05}$	1.5	1.1	1.3			1.3	1.0	1.2		

***Source:** compiled by the authors*

At growth stage 1, developmental phase BBCH 18 (development of leaf rosette), the average dry matter yield of white mustard varieties was 3.89-3.90 t/ha and increased by stage 5 (inflorescence), BBCH 50 (flower buds covered with leaves) by 0.46-0.57 t/ha. The highest increases were observed in stage 6 of growth (flowering), the BBCH development phase, respectively, by 0.79-0.83 t/ha (Table 2).

***Table 2**. Dry matter content of white mustard varieties by growth stages and phases of development (2021-2023), t/ha*

Growth stage, developmental phase (BBCH)	Variety, year									
	Ariadna			mean	± to control	Bila Pryntsesa			mean	± to control
	2021	2022	2023			2021	2022	2023		
1, BBCH 18	4.01	3.67	3.95	3.89	–	4.09	3.85	4.05	3.90	–
5, BBCH 50	4.59	4.08	4.39	4.35	0.46	4.65	4.37	4.39	4.47	0.57
6, BBCH 65	4.78	4.48	4.68	4.68	0.79	4.94	4.53	4.70	4.73	0.83
$LSD_{0.05}$	0.15	0.25	0.20			0.13	0.21	0.18		

***Source:** compiled by the authors*

The chemical composition of the aboveground vegetative biomass shows a low level of crude protein – 3.6% (Ariadna variety) – 3.7% (Bila Pryntsesa) and sugar, respectively, 0.6% and 0.5% (Table 3). The fat content averaged 1.2%, fibre – 12.1%, nitrogen-free extractables – 14.7%, ash – 3.5%, and water – 64.5%.

***Table 3**. Chemical composition of aboveground vegetative biomass of white mustard in the 6th stage of growth (flowering), developmental phase BBCH 65 (2021-2023), %*

Indicator	Cultivar		Mean
	Ariadna	Bila Pryntsesa	
Crude protein	3.6	3.7	3.7
Sugar	0.6	0.5	0.6
Fat	1.2	1.2	1.2
Fibre	12.1	12.0	12.1
REM	14.5	14.8	14.7
Ash	3.4	3.5	3.5
Water	64.6	64.3	64.5

***Source:** compiled by the authors*

In the phase of full flowering, the weight of a white mustard plant of the Ariadna variety was 21.0 g, including 16.6 g of aerial parts and 4.5 g of roots, and 21.2 g of the Bila Pryntsesa variety, respectively, including 17.0 g and 4.2 g (Table 4). The mass of root residues was 9.9-10.1 t/ha, and the vegetative part of plants was 37.1-37.8 t/ha. With a green mass content of 0.11 units/kg and 0.14 g/kg of digestible protein, white mustard provided 4.081-4.158 t/ha of feed units and 5.194-5.292 t/ha of digestible protein (Fig. 3).

Table 4. Structure of white mustard plants in the 6th stage of growth (flowering), developmental phase BBCH 65 (2021-2023)

Indicator	Variety, year							
	Ariadna				Bila Pryntsesa			
	2021	2022	2023	mean	2021	2022	2023	mean
Plant weight, g	19.3	22.4	21.3	21.0	19.7	22.6	21.3	21.2
incl. roots	4.3	4.7	4.4	4.5	4.1	4.5	4.0	4.2
incl. vegetative part	15.0	17.7	17.1	16.6	15.6	18.1	17.3	17.0
Weight of root residues in the soil, t/ha	9.4	10.9	10.0	10.1	9.5	10.4	9.8	9.9
Weight of the aboveground part of plants, t/ha	35.8	38.2	37.4	37.1	36.2	39.5	37.6	37.8

Source: *compiled by the authors*

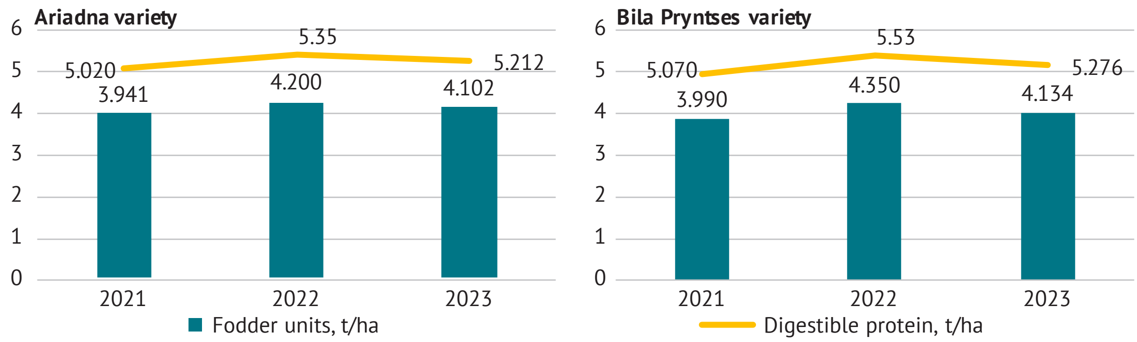

Figure 3*. Indicators of fodder value of white mustard varieties (2021-2023)*
Source: *compiled by the authors*

Considering the current trends in farming, mustard should take a prominent place in Ukrainian agricultural production due to its set of economically valuable attributes. It is a cheap and effective means of fertilising the soil as a green manure crop. Seeds (almost 100% of use) are used in many industries. The by-product is mustard meal, which, after degreasing and grinding, is converted into mustard powder, a product that is valued in the domestic and foreign markets. The oil is used in the food, confectionery, canning, margarine, soap, perfume, and paint industries. The natural antiseptic properties caused by the specific chemical composition and presence of essential oil allow using it in medicine due to its high content of biologically active substances necessary for our body (vitamins (A, D, E, K), fatty acids, phytosterols, chlorophyll, phytoncides, etc.) Linoleic and linolenic essential fatty acids improve the functioning of the cardiovascular system, normalise fat metabolism, maintain hormonal balance, help strengthen the immune system, and neutralise the harmful effects of toxins. Ukraine has all the prerequisites for growing this crop: fertile land, favourable climatic conditions and a rich scientific base, which makes it possible to successfully compete with the European market (Sluchak *et al.*, 2021).

Different types of mustard are the subject of a series of studies in many countries around the world. For instance, T.V. Melnichuk *et al.* (2023) argued that mustard has a high genetic potential for seed productivity, which can be realised by optimising elements of cultivation technology. A balanced nutrition system that combines pre-sowing mineral fertilisation with foliar application of water-soluble fertilisers has a major impact on the formation of productivity elements and biological yield. The combination of $N_{45}P_{45}K_{45}$ and two feedings in BBCH microphases 21-23 and 50-53 with a mixture of urea and complex fertiliser Quantum provides the largest number of seeds on a plant and their weight. O.G. Zhuikov and T.A. Khodos (2021) argue that after mustard as a precursor, grain yields increase by 10-15% without additional costs, which contributes to an increase in crop rotation productivity and efficiency in general. B. Utomo (2022) found a positive effect of NPK on the nutrition of green mustard (*Brassica juncea* L.) plants in studies conducted at the Faculty of Agriculture, Mayjen Sungkono University Mojokerto, Indonesia. The study of the effectiveness of different rates of NPK fertiliser application on the growth and yield of this crop revealed changes in plant length, number of leaves and green mass at the highest rate of 350 kg/ha.

Investigating the effectiveness of mustard cultivation under tillage systems, L.V. Hubenko and O.Ya. Liubchych (2020) established that the highest structure indicators and yield of 2.06 t/ha of this crop were obtained with shelf cultivation and the rate of mineral fertiliser application – $N_{60}P_{60}K_{60}$, while the organic-mineral fertilisation system reduced plant height by 7% and the number and weight of seeds per plant by 5% and 12%.

The productivity of mustard (*Brassica juncea* L. Czern & Coss) cultivar Pusa Vijay was studied at the Crop Production Research Centre, Sardar Vallabhbhai Patel University of Agriculture and Technology, Mirut (UK) on a drained sandy loamy soil with low organic carbon and available nitrogen, medium available phosphorus, potassium, sulphur, and zinc, and moderately alkaline pH. The application of 100% NPK&S + nano Zn spray resulted in maximum yield and oil content (Verma *et al.*, 2022).

In general, all researchers note the significance of investigating a series of elements of white mustard cultivation technology: specifically, varietal assortment, plant nutrition system, protection against diseases and pests, etc., which are narrow and insufficiently covered in scientific publications and require an extended and comprehensive study.

CONCLUSIONS

The sod-podzolic soils of the Carpathian region of Ukraine are poor in nutrients with a humus content of 0.5-2.5% in the topsoil. The reaction of the soil solution makes them acidic, which is one of the significant drawbacks to obtaining high crop yields. Increased acidity has a negative impact on all soil processes: it inhibits the development of soil microflora and nitrogen-fixing bacteria, increases the harmfulness of mobile aluminium, and delays root growth, resulting in lower yields. As a green manure crop, white mustard has a direct impact on increasing the humus content of the soil and allows it to replenish its upper layers with fresh organic matter. Considering the specialisation of the Carpathian region as a livestock area, it is also a significant fodder crop that is well eaten by various species of animals.

Climatic conditions with sufficient moisture supply and high average daily temperature in spring and summer, cause the phenological phases of white mustard to pass more intensively and meet the biological requirements of growing the crop, while the latest developments in domestic breeding allow fulfilling the biological potential of varieties for both seeds and green mass.

It was found that the varieties of white mustard: Ariadna and Bila Pryntsesa leave about 9.9-10.1 t/ha of root residues in the soil and form a high yield of green mass – 37.1-37.8 t/ha, which can be used for green fertiliser at the 6th stage of growth (flowering) of the BBCH 65 phase (full flowering: 50% of the flowers on the main raceme are open, old petals have fallen off). White mustard is somewhat inferior to conventional fodder crops in terms of its biomass chemical composition, but when mixed with high-protein crops, it can provide balanced animal feed.

In the 6th stage of growth (flowering), the phase of development of BBCH 65 varieties of white mustard provided 4.081-4.158 t/ha of feed units and 5.194-5.292 t/ha of digestible protein. Considering the inclusion in the State Register of Plant Varieties Suitable for Distribution in Ukraine of varieties that provide higher productivity of green mass and seeds and are more environmentally plastic, it is advisable to increase the area under white mustard in different soil and climatic zones of Ukraine. Increasing seed production will help to increase the share of this crop in the structure of sown areas. Therefore, further research should focus on the introduction of new varieties of the originator institutions located in the service area of farms and the study of effective methods of their cultivation.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Sinapis alba L. важлива сидеральна та кормова культура в умовах Карпатського регіону України

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Анотація. Гірчиця біла важлива сидеральна і кормова культура в Карпатському регіоні. Мета досліджень полягала у визначенні показників кормової продуктивності та хімічного складу корму сортів гірчиці білої, рекомендованих для вирощування в досліджуваній ґрунтово-кліматичній зоні. Методологічну основу становили загальнонаукові та спеціальні методи досліджень. Подані в статті результати досліджень за 2021-2023 рр. висвітлюють питання динаміки накопичення вегетативної маси й сухої речовини гірчиці білої в різні основні стадія росту та фази розвитку (BBCH) та хімічного складу корму. Дослідженнями встановлено, що зміни клімату, які спостерігаємо в останні роки з підвищеним температурним режимом і достатньою кількість опадів відповідають біологічним вимогам вирощування культури, а створені високопродуктивні сорти забезпечують вимоги сільськогосподарського виробництва як насіння, так і зеленої маси. Встановлено, що на 1 га сорти Аріадна і Біла Принцеса залишають в ґрунті біля 9,9-10,1 т/га кореневих решток та формують високу врожайність зеленої маси (37,1-37,8 т/га), яка може бути використана на зелене добриво в шостій стадії росту (цвітіння) фази BBCH 65 (повне цвітіння: 50 % квіток на головній китиці відкрито, старі пелюстки опали). Хоча за хімічним складом біомаси, досліджувана культура, дещо поступається традиційним кормовим та в суміші з високобілковими може забезпечувати збалансований корм. У основній шостій стадії (цвітіння), фазі розвитку BBCH 65 цінність сортів складала 4,081-4,158 т/га кормових одиниць і 5,194-5,292 т/га перетравного протеїну. Результати досліджень можуть бути використані сільськогосподарськими підприємствами та фермерськими господарствами як на сидерати, так і на корми, що дозволить підвищити родючість ґрунтів та покращити систему живлення тварин

Ключові слова: гірчиця біла; сорт; зелена маса; кормова одиниця; перетравний протеїн; якість

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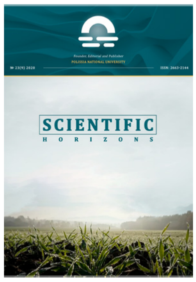

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The effect of humic growth stimulants on the productivity of chickpea (*Cicer arietinum* L.) varieties

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Abstract. In organic farming, the use of plant growth biostimulants in crop cultivation technologies, including chickpea, has become widespread. The purpose of this study: to investigate the manifestation of productivity elements and the yield of chickpea varieties depending on the treatment with an organic growth stimulator. The study employed the following methods: field – to determine the level of yield, laboratory – to investigate the elements of productivity of chickpea, and statistical – to assess

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the reliability of experimental studies. By treatment options, the complex application of the product during pre-sowing seed treatment and foliar feeding of plants during the growing season was distinguished. The effect of organic growth stimulant on the increase of productivity elements of chickpea in this variant of the experiment was noted by an average of 10.0%. The greatest effect of the preparation was found in the complex treatment of seeds and plants of common chickpea in terms of seed weight per plant (24.0%). They were identified by the influence of varietal properties on the productivity elements of common chickpea varieties Triumf and Pamiat. The Pamiat variety with the seed treatment + foliar dressing variant was the best in terms of chickpea yield, but the Triumf variety had the greatest effect of the growth stimulator on the yield increase. Close correlations were found between seed weight per plant and thousand-kernel weight, number of beans per plant and number of seeds per plant, and yield with plant productivity and thousand-kernel weight. The findings of the study are recommended to be used to adjust the elements of chickpea cultivation technology to increase productivity in production conditions

Keywords: seed treatment; foliar feeding; yield; productivity elements

INTRODUCTION

The increase in the cost of mineral fertilisers and plant protection products has led to the search for other sources of nutrients, using natural and synthetic growth regulators that are safer for the environment, which allows for greater use of the biological potential of the crop. O.I. Tsyliuryk (2019) and O.I. Tsyliuryk *et al*. (2022) argue that to optimise plant productivity, it is necessary to use new generation biological plant growth stimulants that accelerate growth processes, increase adaptive capacity, and increase the productive potential of the crop as a whole.

To improve the efficiency of breeding work, Ukrainian scientists have developed variety models for each soil and climatic zone, as highly productive samples in one zone do not always have positive results in other growing zones. Therefore, O.V. Tryhub *et al*. (2020) recommend developing a series of crops for each soil and climatic zone. M.O. Kolesnikov and T.R. Kadyrov (2022) highlight well-known Ukrainian chickpea breeders who have created varieties of chickpea with high adaptive capacity, drought resistance, suitability for mechanised harvesting and disease resistance, as well as a yield potential of 2-3 t/ha.

M.I. Kondratenko *et al*. (2020) address the model of the chickpea variety of the Selection and Genetic Institute, which makes provision for the selection of such indicators as small leaves, compressed bush, tall height of the lower bean, thousand-kernel weight over 400 g and, accordingly, a high yield. D.D. Verma *et al*. (2020) recommend using a model with a high cultivar technology: the height of the lower bean is above 25 cm; the plant height is 50-65 cm to obtain a high yield.

N.O. Vus and L.N. Kobyzieva (2018) highlight the indicators of the large number of beans per plant and seed size. However, chickpea varieties with a large seed weight are demanding on growing conditions, and therefore their resistance to adverse environmental factors must be considered. According to their research, it was found that two varieties of chickpea of the kabuli type combine about seven economically valuable traits. The Ukrainian variety Rosanna is characterised by high levels of drought resistance, ascochyta leaf blight resistance, productivity, thousand-kernel weight, boiling rate, protein content, and a positive reaction to nitraginisation. A sample of Azerbaijani origin was selected for the following traits: drought resistance, resistance to ascochyta leaf blight, seeds per plant, yield level, and cooking property.

O.O. Khodanitska *et al*. (2021) argue that the use of growth stimulants increases the yield of field crops, including chickpeas. There are preparations of natural origin. The use of plant growth stimulants provides a yield increase of up to 20%. These researchers found that to activate the germination of legume seeds, this group of preparations is used by means of pre-sowing seed treatment. The number of sprouted seeds under the treatment with growth stimulants was higher by 3-5 pcs. in bean samples compared to the control. D. Kaur and P. Singh (2020) investigated the impact of biological products on increasing crop yields, which is effective from both an environmental and economic standpoint. According to their findings, chickpea samples with seed inoculation exceeded the control samples by 15.3-15.5% in terms of yield. The researchers confirm the effectiveness of using new generation growth regulators to increase agricultural production.

I.V. Nepran *et al*. (2021) found that pre-sowing treatment showed a positive effect of growth stimulants on pea productivity. According to the findings of the cited study, pre-sowing treatment of pea seeds with Emistim C increased the intensity of both growth processes and plant height by 1.1-1.2 cm per day. The use of humic preparations in studies with sowing samples contributed to an increase in yield compared to the control. An increase in the yield of spring vetch by 10-15% was found with the use of Triman and Humisol growth stimulants. Many studies have confirmed that high-quality seed is the key to high yields of field crops. A.V. Bahan *et al*. (2020) note the significance of foliar feeding of plants as the most common measure of plant protection against pests. At the same time, the findings of their study revealed an increase in the elements of seed productivity of chickpea by 3.6-17.5% in the variant of seed inoculation with Biomag chickpea preparation compared to the control.

S.O. Yurchenko *et al.* (2021) state that the use of the humic preparation 1R Seed treatment resulted in an increase in field germination of peanut varieties by 7.5-18.3%. Under the influence of this preparation on the duration of the interphase period "sowing-sprouting", it was found to be reduced by 3-5 days compared to the control. The effectiveness of the 1R Seed treatment growth stimulant contributed to the friendly germination and healthy plants.

The effectiveness of plant growth stimulants is influenced by a series of factors, including variety properties, methods and timing of application, and growing conditions. Therefore, the study of the impact of this group of products on plant productivity in a particular climate zone is a relevant task. The purpose of this study was to investigate the effect of growth stimulant on the processes of productivity formation of chickpea in the Central Forest-Steppe of Ukraine.

MATERIALS AND METHODS

The study was conducted in 2021-2023 in the Central Forest-Steppe of Ukraine (Poltava region). The research material was four varieties of common chickpea from the Breeding and Genetic Institute of the National Centre for Seed Science and Variety Studies of the National Academy of Agrarian Sciences of Ukraine: Budzhak, Triumf, Pamiat, Odysei. The research design included the following variants: control (no treatment); seed treatment; foliar dressing; seed treatment + foliar dressing. Seed treatment and foliar dressing were performed with an organic growth stimulant of humic origin from Soil-Biotics (USA) – Foliar Concentrate. The seeds were treated before sowing with this product at a rate of 0.6 kg/t. The plants were fertilised in the budding phase at a rate of 2.0 kg/ha. The climate of this region is temperate continental with high temperatures and unevenly distributed precipitation during the spring and summer. The amount of precipitation during the year is 450-550 mm. The soils are typical chernozems, characterised by intensive accumulation of humus and nutrients, medium-grained structure, and shallow carbonates. The humus content in the topsoil is 3.8-4.3%.

During the study, winter wheat was the predecessor. Sowing was performed in the optimal time for the crop – the first decade of April. The sowing method is conventional row sowing with a row spacing of 15 cm. The registered area of the plot was 25 m^2. The replication was fourfold. The location of the plots in the experiment was systematic. The technology of chickpea cultivation was generally accepted and did not differ by experimental variants, except for the type of treatment with the growth stimulator Foliar Concentrate.

During the experiment, the following research methods were employed: field – to determine the level of chickpea yield by experimental variants; laboratory – to determine the elements of productivity of chickpea plants by the factors under study; statistical – to determine the least significant difference (LSD_{05}) according to the method of analysis of variance and to establish the relationship between the elements of productivity, and the level of chickpea yield according to the method of correlation and regression analysis. The research variants were studied according to the following indicators: plant height (cm), beans per plant (pcs.), seeds per plant (pcs.), seeds per bean (pcs.), weight of seeds per plant (g), thousand-kernel weight (g), and yield (t/ha). The level of yield of chickpea by experimental variants was determined according to the method of continuous accounting. The data obtained from the laboratory and field studies was analysed using the statistical analysis package "Statistica 12.0" (Yeshchenko *et al.*, 2014).

The weather conditions during the surveys had minor deviations compared to the long-term average. In terms of moisture and temperature conditions, favourable conditions for chickpea cultivation during the growing season were in 2022, which provided satisfactory conditions for the formation of high productivity. Worse weather conditions were observed in 2023 due to insufficient precipitation in the second half of the growing season. Experimental plant research, including the collection of plant material, was in line with institutional, national, and international guidelines: The Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1979).

RESULTS

According to the research results, the level of manifestation of productivity elements of chickpea by the variants of the experiment was determined (Table 1).

***Table 1**. Productivity elements of chickpea (Cicer arietinum L.) (average for 2021-2023)*

Variety (factor A)	Treatment variant (factor B)	BP, cm	CBD, pcs.	SPB, pcs.	SPP, pcs.	SWP, g	TKW, g
Budzhak	control	59.0	52.0	1.08	56.2	16.5	276.0
	seed treatment	63.1	56.3	1.12	63.1	17.5	281.8
	foliar dressing	66.0	58.7	1.16	68.1	18.8	286.2
	seed treatment + foliar dressing	68.1	59.6	1.18	70.3	19.3	290.8

Table 1. Continued

Variety (factor A)	Treatment variant (factor B)	BP, cm	CBD, pcs.	SPB, pcs.	SPP, pcs.	SWP, g	TKW, g
Triumf	control	72.2	61.0	1.12	68.3	16.1	252.1
	seed treatment	76.3	63.8	1.18	75.3	17.0	258.5
	foliar dressing	78.3	65.6	1.23	80.7	18.1	264.0
	seed treatment + foliar dressing	81.1	67.3	1.25	84.1	18.9	268.7
Pamiat	control	71.7	55.3	1.07	59.2	18.3	322.4
	seed treatment	75.7	58.5	1.13	66.1	19.2	329.8
	foliar dressing	79.8	60.2	1.17	70.4	20.5	337.2
	seed treatment + foliar dressing	81.6	61.0	1.20	73.2	21.3	342.0
Odysei	control	56.5	59.0	1.03	60.8	16.8	283.2
	seed treatment	59.8	62.3	1.07	66.7	18.0	289.8
	foliar dressing	61.5	65.6	1.12	73.5	19.2	295.4
	seed treatment + foliar dressing	63.6	66.2	1.14	75.5	20.0	299.7
mean		*69.6*	*60.8*	*1.14*	*69.5*	*18.5*	*292.4*

Notes: *PH – plant height, BPP – beans per plant, SPB – seeds per bean, SPP – seeds per plant, SWP – seed weight per plant, TKW – thousand-kernel weight*
Source: *compiled by the authors of this study*

According to the average data, the lowest value for the studied indicators was found in the control variant, and the highest – in the variant of seed treatment + foliar feeding, which indicates the effectiveness of the growth stimulator Foliar Concentrate during the complex treatment of seeds and plants. The height of the plant varied within 56.5-81.6 cm according to the experimental variants. Treatment of undersized chickpea varieties Budzhak and Odysei with the preparation according to the variant of seed treatment + foliar dressing, compared to the control, increased the plant height by 9.1 cm and 7.1 cm, respectively. In the taller varieties Triumf and Pamiat, this figure increased by 8.9 cm and 9.8 cm, respectively.

The number of beans per plant was within 52.0-67.3 pieces. On average, this indicator increased by 6.7 units in the experiment when using the growth stimulator in the variant of seed treatment + foliar dressing. The largest number of beans per plant was observed in the Triumph variety – 67.3 pieces. The number of seeds per bean, as a varietal trait, varied within insignificant limits and was equal to 1.03-1.25 pieces. Complex treatment with the product helped to increase this indicator by an average of 0.12 pieces. The Triumf chickpea variety had the highest number of seeds per bean – 1.25 pieces. The number of seeds per plant depends on the number of seeds in the bean, which was 56.2-84.1 seeds, respectively. In the variant of seed treatment + foliar feeding, the number of seeds per plant increased by 12.1 pieces on average. The Triumf chickpea variety was also distinguished by this indicator (84.1 pcs).

The seed weight per plant varied within 16.1-21.3 g. Integrated processing contributed to an average increase of 2.9 g. The highest plant productivity was observed in the Pamiat chickpea variety – 21.3 g. The thousand-kernel weight in the experimental variants was 252.1-342.0 g, respectively. The use of this preparation in the variant of seed treatment + foliar dressing allowed increasing the indicator under study by an average of 16.8 g. The largest thousand-kernel weight was that of the Pamiat chickpea variety – 342.0 g. Figure 1 shows the effect of growth stimulant on the level of manifestation of productivity elements of chickpea by treatment variants compared to the control.

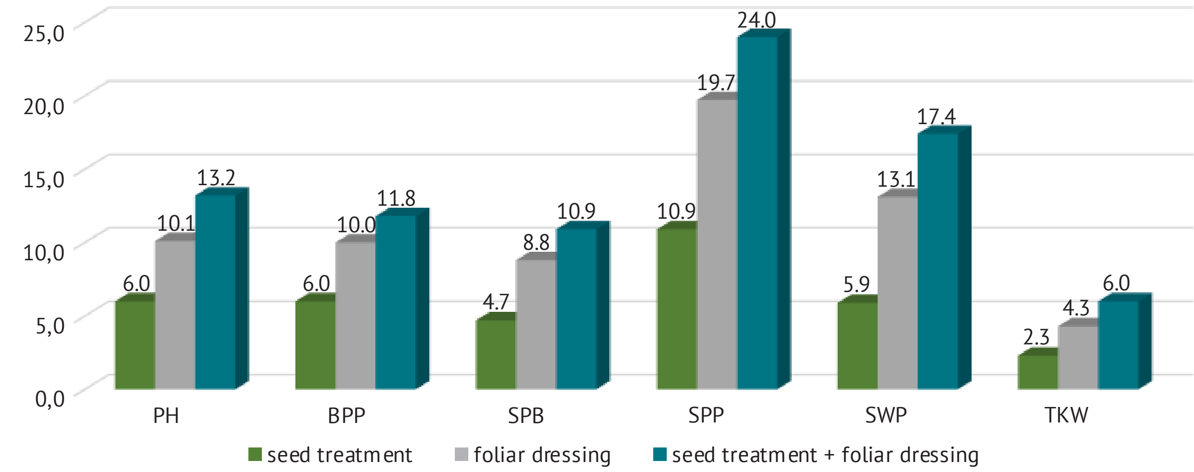


***Figure 1**. Effect of the preparation on the increase of chickpea productivity elements by treatment variants compared to the control, %*

***Note:** PH – plant height, BPP – beans per plant, SPB – seeds per bean, SPP – seeds per plant, SWP – seed weight per plant, TKW – thousand-kernel weight*

***Source:** compiled by the authors of this study*

According to Figure 1, the test preparation influenced the increase in the studied parameters as follows: plant height – by 6.0-13.2%, beans per plant – by 6.0-11.8%, seeds per bean – by 4.7-10.9%, seeds per plant – by 10.9-24.0%, weight of seeds per plant – by 5.9-17.4%, thousand-kernel weight – by 2.3-6.0%. The complex treatment with a growth stimulator increased the manifestation of all parameters under study, except for the thousand-kernel weight, by more than 10.0%. The index of seed weight per plant in this variant of the experiment increased by 24.0%. This suggests the effect of this product on plant height and fruit and seed formation during the growing season. According to the results of the correlation analysis, a strong correlation was found between the following indicators: thousand-kernel weight and weight of seeds per chickpea plant (r = 0.77), as well as the number of beans per plant and the number of seeds per chickpea plant (r = 0.91) (Fig. 2).

According to Figure 2, the effect of the growth stimulant on increasing the water content of chickpea plants per plant and increasing productivity per plant was noted. Yields varied slightly over the years of research: 2021 – 0.98-2.43 t/ha, 2022 – 1.17-2.57 t/ha, 2023 – 0.82-2.09 t/ha. The highest level of chickpea yields was recorded in 2022 (Table 2).

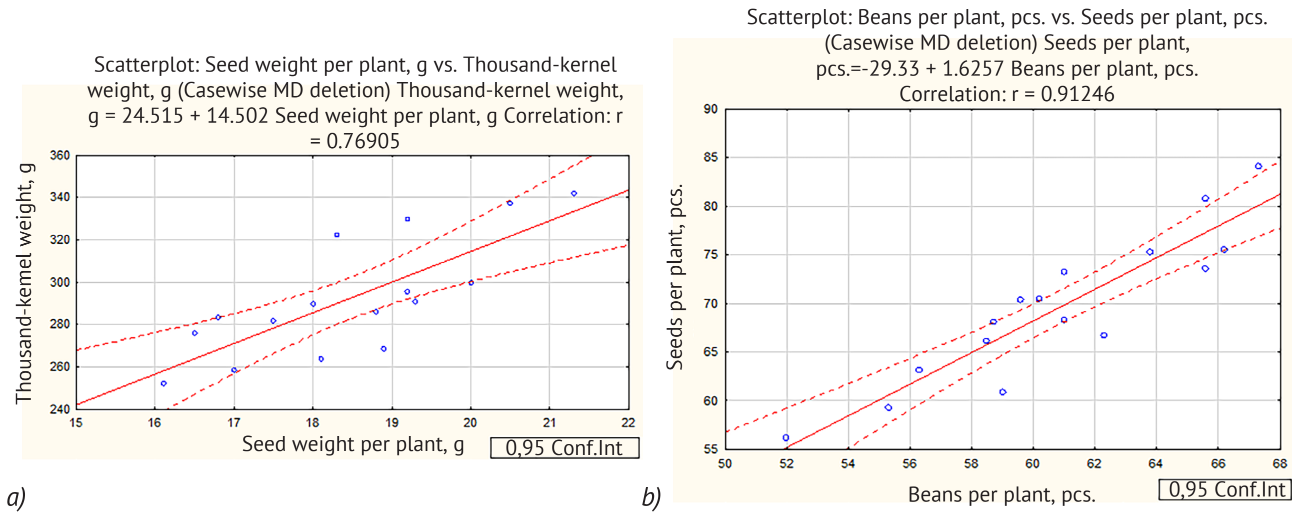


***Figure 2**. Correlation of productivity elements of chickpea*

***Note:** a) correlation between thousand-kernel weight and weight of seeds per plant; b) correlation between number of beans per plant and number of seeds per plant*

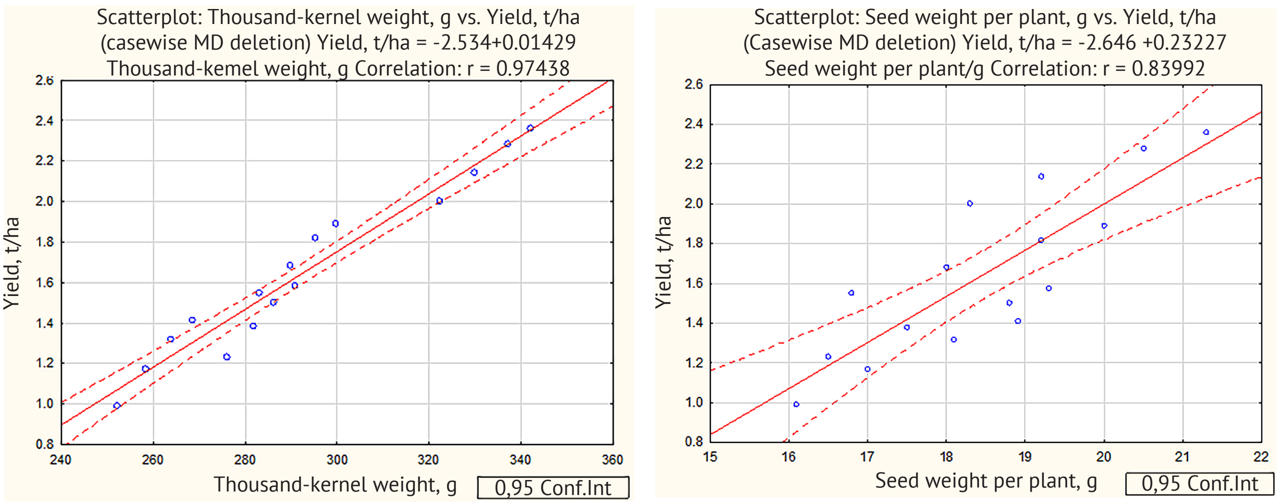
***Source:** developed by the authors of this study*

***Table 2**. Yield of common chickpea (Cicer arietinum L.)*

Variety (factor A)	Treatment variant (factor B)	Yield, t/ha				
		2021	2022	2023	*mean*	*deviation ±*
Budzhak	control	1.22	1.46	1.01	*1.23*	–
	seed treatment	1.35	1.59	1.19	*1.38*	*+0.15*
	foliar dressing	1.48	1.70	1.32	*1.50*	*+0.27*
	seed treatment + foliar dressing	1.56	1.77	1.41	*1.58*	*+0.35*
Triumf	control	0.98	1.17	0.82	*0.99*	–
	seed treatment	1.15	1.38	0.97	*1.17*	*+0.18*
	foliar dressing	1.29	1.52	1.16	*1.32*	*+0.33*
	seed treatment + foliar dressing	1.37	1.60	1.25	*1.41*	*+0.42*
Pamiat	control	2.03	2.24	1.72	*2.00*	–
	seed treatment	2.18	2.38	1.86	*2.14*	*+0.14*
	foliar dressing	2.35	2.50	2.00	*2.28*	*+0.28*
	seed treatment + foliar dressing	2.43	2.57	2.09	*2.36*	*+0.36*
Odysei	control	1.55	1.80	1.30	*1.55*	–
	seed treatment	1.69	1.93	1.41	*1.68*	*+0.13*
	foliar dressing	1.83	2.08	1.54	*1.82*	*+0.27*
	seed treatment + foliar dressing	1.90	2.15	1.62	*1.89*	*+0.34*
	LSD_{05} (A)	0.36	0.41	0.38		
	LSD_{05} (B)	0.20	0.17	0.20		
	LSD_{05} (AB)	0.39	0.43	0.40		

***Source:** developed by the authors of this study*

According to factor A, in 2021-2023, the Pamiat variety substantially outperformed other chickpea varieties in terms of yield. According to factor B, the yield of chickpea after complex treatment with a growth stimulator substantially exceeded this indicator in the control and pre-sowing seed treatment variants. According to the average yield data, the treatment variants exceeded the control by 0.15 t/ha, the foliar dressing option – by 0.29 t/ha, and the seed treatment + foliar dressing variant – by 0.37 t/ha. The average yield of the Pamiat variety was 2.36 t/ha under the complex treatment with the preparation. In addition, according to average data, the greatest impact of complex stimulant treatment was observed in the Triumph variety – 0.42 t/ha. According to the results of correlation analysis, the interrelations of productivity elements with the level of chickpea yield were established. Close correlations were observed between the following parameters: thousand-kernel weight and yield (r = 0.97), and weight of seeds per plant and yield (r = 0.84) (Fig. 3).



a) *b)*

***Figure 3**. Correlation of productivity elements with the level of chickpea yield*
***Note:** a) relationship between thousand-kernel weight and yield; b) relationship between seeds per plant and yield*
***Source:** compiled by the authors of this study*

According to Figure 3, the effect of the growth stimulator on the increase in the yield level of chickpea due to the increase in seed size and plant productivity was noted. Thus, during the cultivation of chickpea, the usual use of complex treatment of seeds and plants with an organic growth stimulator allows increasing the elements of seed productivity and yield level in the conditions of the Central Forest-Steppe of Ukraine.

DISCUSSION

Many studies have been conducted on the effectiveness of growth stimulants in increasing the productivity of pulses. O. Khodanitska *et al*. (2021) found a positive effect of the use of biostimulants during pre-sowing seed treatment and during the growing season, which suggests analogous conclusions to the studies conducted on the subject investigated in the present study. Studies have established the relationship between the resistance of chickpea plants and other indicators. M.I. Kondratenko *et al*. (2020), in their study of chickpea plants resistance to ascochyta leaf blight, highlighted its strong connection with seed size and duration of interphase periods. The researchers found correlations between the average strength of the cold resistance index and plant height and seed size. In the present study, the interrelationships of the elements of chickpea seed productivity with each other and with the yield index were investigated. Establishing the correlations of these parameters with the duration of interphase periods, cold resistance, and resistance to ascochyta leaf blight was not the purpose of this study.

A.V. Bahan *et al*. (2020), based on the findings of studies on the effect of Biomag chickpea preparation on the elements of seed productivity of common chickpea varieties during pre-sowing seed treatment, indicated an increase in the studied indicators compared to the control. The treatment of chickpea seeds with this preparation contributed to an increase in the following indicators: plant height by 8.4%, the number of beans per plant by 14.4%, the number of seeds per plant by 17.5%, the number of seeds per bean by 3.6%, which suggests the effectiveness of using the Biomag chickpea preparation. The present study established the effectiveness of the use of growth regulators not only for pre-sowing treatment of chickpea seeds, but also for the complex application of the preparation (seed treatment + foliar dressing).

O.V. Ovcharuk *et al*. (2019) found a positive effect of growth regulators on increasing yields by 8-17%. In their study, the researchers point out that the effectiveness of these products depends on a series of factors, namely: varietal properties, processing methods, and growing conditions. I.M. Didur and M.O. Mordvaniuk (2018) and I.M. Didur *et al*. (2020) note that the findings of 2016-2017 studies revealed an increase in the yield of common chickpea under pre-sowing seed treatment with the Biomag chickpea inoculant and two-time foliar dressing of plants with the organic microfertiliser Urozhai Bobovi, compared to the control, which was 0.61 t/ha and 1.12 t/ha, respectively. The researchers noted that when growing common chickpea, the most favourable conditions for yield formation were found during seed treatment with an inoculant and two foliar dressings with microfertiliser in the interphase period "intensive growth – budding".

M. Mordvaniuk *et al*. (2019) also found a positive effect of using inoculation of chickpea seeds with Biomag chickpea and two foliar dressings with Urozhai Bobovi microfertiliser on increasing the yield level by 0.62-0.68 t/ha compared to the control. In the current study, a positive effect of the growth stimulator was noted on both the elements of seed productivity and the level of yield when used in combination with seed treatment and foliar dressing. M.I. Kondratenko *et al*. (2020) established medium-strength correlations between the number of beans per plant and the number of seeds per bean with plant productivity ($r = 0.64$ and $r = 0.56$, respectively), between the weight of seeds per plant and the thousand-kernel weight ($r = 0.65$). A.Ye. Titova (2018) notes strong correlations between the traits of number of beans per plant and number of grains per plant ($r = 0.82$), number of beans per plant and plant productivity ($r = 0.81$), as well as medium strength of the relationship between plant height and seed weight per plant ($r = 0.54$), and therefore, she recommends selecting samples according to the selected traits. The findings of these studies showed a correlation between the thousand-kernel weight and plant productivity ($r = 0.77$), as well as a strong correlation between the number of beans per plant and the number of seeds per plant ($r = 0.91$).

Thus, in the context of climate change, it is necessary to pay attention to some elements of chickpea cultivation technology, in particular the use of humic plant growth stimulants depending on the timing and methods of treatment.

CONCLUSIONS

According to the findings of the study, the effectiveness of the combined use of the preparation during pre-sowing seed treatment and fertilisation of chickpea plants during the growing season was established. This treatment variant contributed to an increase in the manifestation of productivity elements of chickpea by more than 10.0% compared to the control (without treatment). The indicator of seed weight per plant in this variant of the experiment increased by 24.0%. Among the varietal composition, the Pamiat chickpea variety can be distinguished by such productivity elements as plant height, seed weight per plant, and thousand-kernel weight. According to the level of manifestation of biometric parameters, the Triumf chickpea variety was distinguished by the number of beans and seeds per plant, the number of seeds per bean. The Pamiat chickpea variety was distinguished by the level of yield under the variant of complex application of the preparation. However, the greatest increase in yield in this variant of the experiment was observed in the Triumf variety (29.8%) compared to the Pamiat variety (15.3%).

Close correlations were established between the weight of seeds per plant and the thousand-kernel weight, as well as beans per plant and seeds per plant. The dependence of chickpea yield on plant productivity and thousand-kernel weight was noted. Thus, the complex use of a growth stimulator contributed to the growth of chickpea yield by increasing plant productivity. The prospect of further research is to investigate the effect of complex application of the growth stimulator Foliar Concentrate on the level of adaptability of chickpea plants.

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None.

CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Вплив гумінових стимуляторів росту на продуктивність сортів нуту звичайного (*Cicer arietinum* L.)

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Анотація. За умов органічного землеробства поширення набуло використання біостимуляторів росту рослин у технологіях вирощування сільськогосподарських культур, зокрема і нуту звичайного. Мета досліджень: вивчення прояву елементів продуктивності та рівня урожайності сортів нуту звичайного залежно від обробки органічним стимулятором росту. Під час досліджень використовували наступні методи: польовий – для визначення рівня урожайності, лабораторний – для вивчення елементів продуктивності нуту звичайного та статистичний – для оцінки достовірності експериментальних досліджень. Було виділено за варіантами обробки комплексне застосування препарату під час передпосівної обробки насіння та позакореневого підживлення рослин у період вегетації. Було відмічено вплив органічного стимулятора росту на збільшення елементів продуктивності нуту звичайного за даним варіантом досліду у середньому на 10,0 %. Було встановлено найбільший вплив препарату за комплексної обробки насіння і рослин нуту звичайного за показником маси насіння з рослини (24,0 %). Було виділено за впливом сортових властивостей на елементи продуктивності нуту звичайного сорти Тріумф і Пам'ять. Було відмічено за показником урожайності нуту звичайного сорт Пам'ять з варіантом обробка насіння + позакореневе підживлення, але найбільший вплив стимулятора росту на приріст урожайності відмічено у сорту Тріумф. Було встановлено тісні взаємозв’язки маси насіння з рослини із масою 1000 насінин, кількості бобів на рослині із кількістю насінин з рослини, а також урожайності із продуктивністю рослини та масою 1000 насінин. Результати дослідження рекомендовано використовувати для корегування елементів технології вирощування нуту звичайного з метою підвищення продуктивності у виробничих умовах

Ключові слова: обробка насіння; позакореневе підживлення; урожайність; елементи продуктивності

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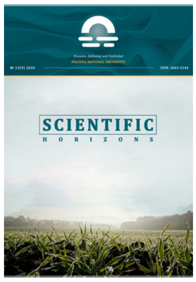

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Assessment of the stability of common winter wheat breeding lines in multi-environment tests

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Abstract. Climate change poses a challenge to agricultural production. To avoid production losses and exploit the emerging potential, adaptation in agricultural management will inevitably be required, in particular through the development of highly adapted and plastic varieties. To obtain wheat varieties combining productivity and stability, in 2018-2021, eight promising breeding lines of common winter wheat were studied in multi-environment eighteen trials at the V.M. Remeslo Myronivka Institute of Wheat of the National Academy of Agrarian Sciences of Ukraine using

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three sowing dates after two preceding crops. Using ANOVA, it was established that environmental conditions had the highest reliable contribution to the yield variation (72.09%), genotype-environment interaction and genotype had significantly less (25.30% and 2.61%, respectively). The sowing dates for the preceding crops had a significant effect on the variation in the line productivity. Higher yields were received after green manure (mustard) in 2019 and 2020. The stable maximum level of productivity in terms of sowing dates was after preceding crop mustard as green manure for sowing on October 5 (the third term) and after maize for silage for sowing on September 25 (the second term). It was found that the conditions of the second sowing date were as an analytical background for selection of high-yielding lines of winter wheat. For practical breeding work, the breeding lines Lutescens 36921, Erythrospermum 36866, Erythrospermum 36802 were selected and released as new varieties Trudovnytsia Myronivska, MIP Vyshyvanka, and Gracia Myronivska, which have high yields and adaptability

Keywords: winter wheat; breeding line; genotype-environment interaction; statistical parameters

INTRODUCTION

The future of climate change and its associated impacts is highly unpredictable, which makes planning for mitigation and adaptation a bit complex. This necessitates the formulation of climate-resilient technologies involving an interdisciplinary approach according to the region. Suitable varieties need to be developed that could adapt to climatic variations, along with planned agronomic management and crop pest control. Farmers need to be educated regarding various climate-smart technologies and be provided training to simplify their use at the field level. Adaptive varieties are more resistant to adverse environmental factors, the influence of which determines up to 60-80% of yield variability between years. Heat stress and heat drought are the major yield limiting factors of wheat that reduces yield up to 24% and 48 %, respectively. Hence, there is a prior need for climate resilient breeding (Cortinovis *et al.*, 2020; Rossnerova *et al.,* 2020; Malhi *et al.,* 2021).

Yield level of the variety is an integrated criterion of its adaptability to specific environmental conditions. In addition to the productivity potential, its stability over the years based on the increased resistance of varieties against complex of limiting environmental factors is important. Yield stability is the major feature of modern wheat breeding programs due to significant fluctuations in average yield, especially under drought conditions. Breeders are working to develop varieties being more resistant and adaptive to environmental changes (Raza *et al.,* 2019; Bocci *et al.,* 2020). M. Roostaei *et al.* (2022) believe that addition of multi-environmental tests in breeding process increases its effectiveness and allows distinguishing the most promising genotypes based on the combination of yielding capacity and stability. In addition, evaluation of breeding lines (genotypes) in multi-environment tests, according to H. Awaad (2021) and S. Mahpara *et al.* (2022), allows obtaining the most complete information about yielding capacity and stability of breeding material.

T. Olivoto *et al.* (2019), B. Vaezi *et al.* (2019) note that in multi-environment trials (MET) when a set of genotypes is tested (examined) in a set of environments (locations, years, or its combination), the main purpose of plant breeding is to recommend genotypes for specific environments or to discriminate these mega-environments. Successful (innovative) varieties must be adapted to a wide range of environmental conditions for stable fulfilment of their genetic potential and effective use of crop management systems. The yield of each variety in any environment is the sum of the environment main effect (E), the genotype main effect (G) and the genotype × environment interaction (GE or GEI) (Pourdad & Moghaddam, 2020). Increasing the adaptability of varieties with stable yielding capacity and product quality in the genotype-environment interaction (GEI) is still a leading problem of breeders. As a component of the total phenotypic variance, GEI negatively affects heritability. A high effect of GEI leads to a lower heritability, thus breeding progress will be limited. Genotype-environment interaction (GEI) complicates the process of selecting better genotypes (Xiong *et al.,* 2020; Naik *et al.,* 2022). GEI can be divided into two groups: cross qualitative interaction (when genotype ranks change from one environment to another) and uncrossed quantitative interaction (changes in genotype productivity value without a change in the rank order of the genotypes in various environments). In this context, if the response of a genotype to the environment parallels the average response of all genotypes, it is identified as stable (Kang, 2020).

Existing methods for determining stability (regression analysis, non-linear regression analysis, multivariate analysis, and non-parametric statistics) with the interaction of the genotype with the environment, help breeders to determine the best genotypes for which it is minimal, allow of their phenotypic response to environmental changes (Coan *et al.,* 2022; Pour-Aboughadareh *et al.,* 2022; Bosi *et al.,* 2022). There are two main statistical models and approaches for analysing and interpreting the interaction of genotype with environment. Parametric stability statistics (univariate and multivariate) are mainly used in breeding studies, they are based on distributional assumptions regarding the influence of the environment, genotypes, and their interaction. The second group is non-parametric stability statistics that do not require initial assumptions. Nonparametric statistics are evaluated based on average values of the response and the ranking of the genotypes. Non-parametric statistics are easy to use and facilitate interpretation of the GEI, adding or deleting one or more genotypes has little effect on the results. To analyse the data of multi-environment tests, statistical parameters are used, one of the most well-known is the regression analysis according to S.A. Eberhart and W.A. Russell (1966) and G.C. Tai (1977), which allow identifying three parameters of productivity and environmental stability: the average value of genotype, indicators of linear and non-linear reactions to environment. The main effects and multiplicative interaction (AMMI) and genotype × environment interaction (GGE) biplot models, which are based on the method of principal components, have been widely used to characterise GEI and estimate yield stability (Khan *et al.,* 2021; Adham *et al.,* 2022). AMMI and GGE biplot explain a larger share of genotype-environment interaction compared to statistical parameters.

The purpose of the study was to identify breeding lines of winter common wheat that combine the potential of productivity and stability in years with contrasting weather conditions, when using different preceding crops and sowing dates.

MATERIALS AND METHODS

The study was conducted at the Myroniv Wheat Institute named after V. M. Remeslo of the National Academy of Agrarian Sciences of Ukraine during 2018-2021. The material for the study included the breeding lines of winter wheat in the competitive test: G1 (Podolianka (standard), G2 (Erythrospermum (ER) 36802), G3 (Lutescens (LUT) 36756), G4 (Lutescens 36921), G5 (Erythrospermum 54866), G6 (Lutescens 37090), G7 (Lutescens 528/03), G8 (Lutescens 54875), G9 (Lutescens 36926). Sowing was performed with the seeder SN-10 (Ukraine) with the seeding rate of 5 million viable seeds per 1 ha in three terms (September 15, September 25, October 3–5) after two preceding crops (mustard as green manure (GM), maize for silage (CR)). In general, for three years, yield indicators of lines were obtained in 18 environments (E). Plots were placed systematically, with four replications, sample area was 10 m^2. The crop was direct harvested with the "Hege 125" (Zürn Harvesting, Germany) and transfer to standard (14 %) grain moisture.

Environmental parameters as background for selection, indicators of adaptive capacity and stability of genotypes were determined according to the method of O.V. Kilchevskii and L.V. Khotylyeva (1985). According to this methodology, the differentiating ability of the environment was characterised using the following parameters: productivity (impact) of the environment d_k; the variance of the differentiating ability of the environment $\sigma^2 DAE_k$; differentiating ability of the environment σDAE; indicator of the relative differential ability of the environment S_{ek}; compensation coefficient of the k^{th} environment K_{ek}. To assess the response of breeding lines to changes in environmental conditions, the indicators were determined: general adaptive ability GAA, specific adaptive ability SAA, relative stability of the genotype S_{gi}, indicator of breeding value of the genotype BVG; genotype compensation coefficient C_{gi}; regression coefficient b_i and mean square deviation S^2_{di} (Eberhart and Russel, 1966); coefficient of determination R^2 (Pinthus, 1973); stability variance σ_i^2 (Shukla, 1972); ecovalence W_i (Wricke, 1962); genotype superiority indicator P_i (Lin and Binns, 1988); non-parametric stability indicators $S_i^{(1)}$ and $S_i^{(2)}$ (Huehn, 1990). To rank the lines (R) and determine the adaptability, the method of non-parametric statistics of G.W. Snedecor (1961) was used. The average value ($\overline{X}$) of yield in the experiment and the average numerical value of statistical indicator was used as a basis to compare when analysing. The best value of the parameter corresponds to the number one ranking. The distribution of genotypes by productivity connection and adaptability in multi-environment tests is analysed using the AMMI model, which allows for variance analysis and singular distribution (Gauch, 2013; Negash *et al.,* 2013).

The sowing period 2018-2019 was characterised with severe air-soil drought that continued until mid-October, which negatively affected the initial growth of plants and largely caused the grain loss of winter crops. Meteorological conditions during the years of the study were contrasting, which made it possible to obtain an objective assessment of adaptive properties of the lines under study (Fig. 1).

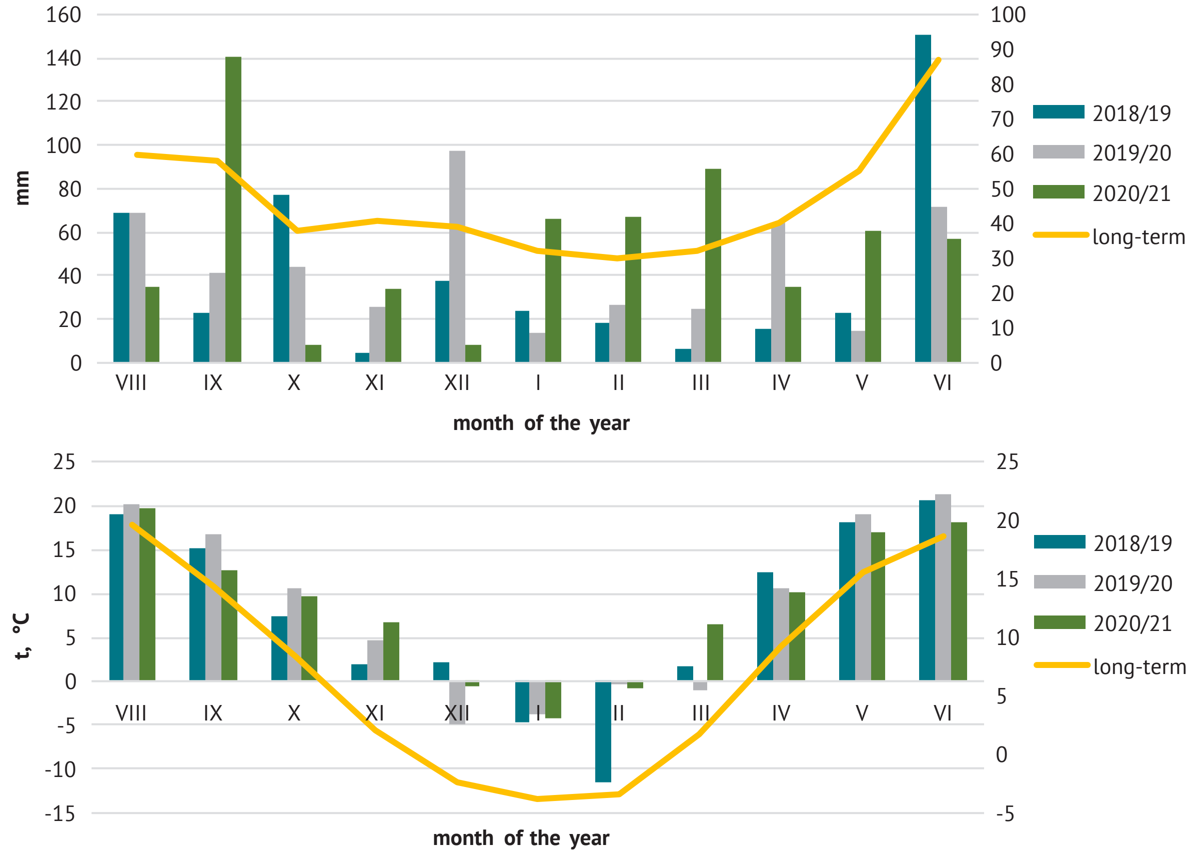

***Figure 1**. Weather conditions of the growing season, 2018-2021*
***Source:** data according to meteostation Myronivka of this study*

The experimental studies of plants (both cultivated and wild), including the collection of plant material, were performed following institutional, national, or international guidelines. The study followed the standards of the Convention on Biological Diversity (1992) and the Convention on Trade in Endangered Species of Wild Fauna and Flora (1979).

RESULTS AND DISCUSSION

The crops of the first sowing period had irregularities in plant growth and development, partially sparse plantings and that also affect the yield of the lines. The condition of crops in the following periods was satisfactory. The increased temperature regime contributed to the slow vegetation of winter crops, which continued until mid-January. The conditions that prevailed during the overwintering period were conducive to the resumption of vegetation, which occurred approximately two weeks earlier than the long-term average.

In the spring, the best indicators of vegetative mass and productivity formation were observed during sowing on September 25 (II) after maize (CR) and on October 5 (III) after mustard (GM). The second half of the growing season took place under elevated temperature regime and sufficient moisture supply. The maximum average yield according to the growing season was obtained for the third sowing period (6.55 t/ha, GM) and the second one (6.77 t/ha, CR). The minimum yield was obtained for sowing in the first term, 5.77 t/ha and 5.27 t/ha, respectively. In general, according to the preceding crops, the average yield was at the same level (Table 1).

***Table 1**. Yield of soft winter wheat breeding lines, 2018-2021*

Code genotype line	Sort, breeding line	Year / sowing dates 2019/13 2020/14									Average value
		2018/2019			2019/2020			2020/2021			
		I*	II	III	I	II	III	I	II	III	
		Mustard as green manure (GM)									
G1	Podolyanka St	5.12	6.01	6.50	3.40	5.26	5.84	4.91	3.61	5.12	5.09
G2	ER 36802	6.38	6.33	6.94	4.38	6.38	6.90	6.48	5.37	6.38	6.17

Table 1. Continued

Code genotype line	Sort, breeding line	Year / sowing dates 2019/13 2020/14									Average value
		2018/2019			2019/2020			2020/2021			
		I*	II	III	I	II	III	I	II	III	
		Mustard as green manure (GM)									
G3	LUT 36756	5.97	6.29	6.36	4.97	6.07	6.76	5.48	3.42	5.97	5.70
G4	LUT 36921	6.06	6.56	6.73	4.67	5.82	5.68	6.44	5.03	6.06	5.89
G5	ER 54866	6.01	5.22	5.77	3.80	6.54	5.91	5.36	4.92	6.01	5.50
G6	LUT 37090	5.83	6.58	6.99	4.39	5.47	6.19	4.86	3.11	5.83	5.47
G7	LUT 528/03	4.80	6.18	6.35	4.17	5.46	6.32	5.27	2.96	4.80	5.15
G8	LUT 54875	6.14	6.31	7.00	3.62	4.51	4.95	6.01	3.69	6.14	5.37
G9	LUT 36926	5.66	5.46	6.28	4.41	5.42	5.71	5.27	3.06	5.66	5.21
Average value		5.77	6.10	6.55	4.20	5.66	6.03	5.56	3.91	5.77	5.51
		Maize for silage (CR)									
G1	Podolyanka St	5.02	6.40	6.21	3.27	5.61	5.68	5.50	4.96	5.20	5.32
G2	ER 36802	5.10	7.14	5.86	3.13	6.34	5.80	6.23	6.75	6.56	5.88
G3	LUT 36756	5.42	7.13	6.41	4.45	6.60	5.28	6.42	8.30	6.79	6.31
G4	LUT 36921	5.79	6.69	6.66	3.89	4.80	4.97	5.76	6.85	5.53	5.66
G5	ER 54866	5.00	6.42	6.56	4.32	6.34	5.97	5.83	6.83	6.36	5.96
G6	LUT 37090	5.37	7.19	6.60	3.89	5.70	5.39	6.22	6.65	6.24	5.92
G7	LUT 528/03	5.00	6.65	6.47	3.82	4.85	5.91	5.26	6.36	5.91	5.58
G8	LUT 54875	5.29	6.70	6.82	3.12	4.84	5.64	5.40	5.75	5.90	5.50
G9	LUT 36926	5.48	6.59	6.40	4.11	5.59	5.20	4.62	6.39	5.63	5.56
Average value		5.27	6.77	6.44	3.78	5.63	5.54	5.69	6.54	6.01	5.74
Average value		5.52	6.43	6.50	3.99	5.64	5.78	5.62	5.22	5.89	5.62
Average value			6.15			5.13			5.58		5.62
LSD_{05}			0.84			0.72			1.10		0.80

Note: ** – sowing dates: I – September 15, II – September 25, III – October 5*
Source: *compiled by the authors of this study*

In 2019-2020, the post-sowing period was wet, which had a positive effect on the emergence of seedlings and the density of plant stands. Unstable temperature conditions were observed in winter. The amount of precipitation exceeded the average every month. After the snowfall, areas of snow mould (within 5-25%) and rotting (or asphyxiation) were found on the winter crops, which led to their sparseness, especially for the first sowing period. During the late spring vegetation resumption (April 1, two days later than the long-term date), the duration of forced winter dormancy was the longest, which had a negative impact on the growth, development, and productivity of plants (crops were sparse, plants were weakened). The weather conditions of the spring-summer period had more negative influence on the formation of yielding capacity (a sharp drop in the temperature regime and deficiency of effective rainfall). The higher yield of the line was formed after green manure (GM). The maximum yield after GM was obtained for the third sowing period (6.03 t/ha) and after maize for the second and third one (5.63 t/ha and 5.54 t/ha, CR). The minimum yield was obtained for the first sowing period (4.20 t/ha and 3.78 t/ha after GM and CR, respectively).

The growing season of 2020-2021 was specific with untypical cool weather with excessive rainfall during the sowing period (September), which delayed grain germination and the emergence of winter wheat seedlings. A relatively warm winter and the significant intense rainfall in May led to lodging, and complicate grain ripeness. The weather conditions of the spring-summer period (early resumption of spring vegetation; absence of long dry periods) contributed to the formation of high yield of winter wheat grain. The level of productivity after green manure (GM) for the first and third sowing dates was at almost the same level (5.56 t/ha and 5.77 t/ha). The minimum yield according to the growing season (3.91 t/ha, GM, the second sowing period) was formed as a result of the sharp decrease in air temperature, oversaturation of soil moisture, and the increase in its density during sowing, which caused delay in seedling emergence, decrease in plant density and led to their weak growth and development as compared to other sowing dates. Grain yield after maize (CR) according to the sowing dates was 5.69 t/ha, 6.54 t/ha, and 6.01 t/ha, respectively. Summarising the findings of the study, the variability of plant vegetation conditions in different growing seasons significantly affected the yield of breeding lines of winter common wheat. The minimum yield 2.96 t/ha was obtained for G7 (Lutescens 528/03) in the environment E8 (2020-GM-II); maximum yield – 8.30 t/ha was obtained for G3 (Lutescens 36756) in the environment E17 (2021-CR-II).

According to the level of expression and yield stability in combination with other agronomic traits in contrasting conditions in 2018-2021, the breeding lines G5 (Erythrospermum 54866), G2 (Erythrospermum 36802), and G4 (Lutescens 36921) were selected and submitted for State Variety Testing as the new winter wheat varieties MIP Vyshyvanka, MIP Hratsiia and Trudivnytsia Myronivska. According to the growing seasons, for the two preceding crops the highest average yield (6.15 t/ha) was obtained in the relatively favourable 2018-2019 (albeit under elevated temperature regime but with sufficient moisture supply), the lowest average yield (5.13 t/ha) was obtained in 2019/20 because of drought during the grain filling period. According to the preceding crops, the average yield of the breeding lines was higher (by 1.10 t/ha) after maize for silage (CR) in the more humid autumn and summer periods of 2020-2021. Sowing dates affected the increase in yield variability (Fig. 2).

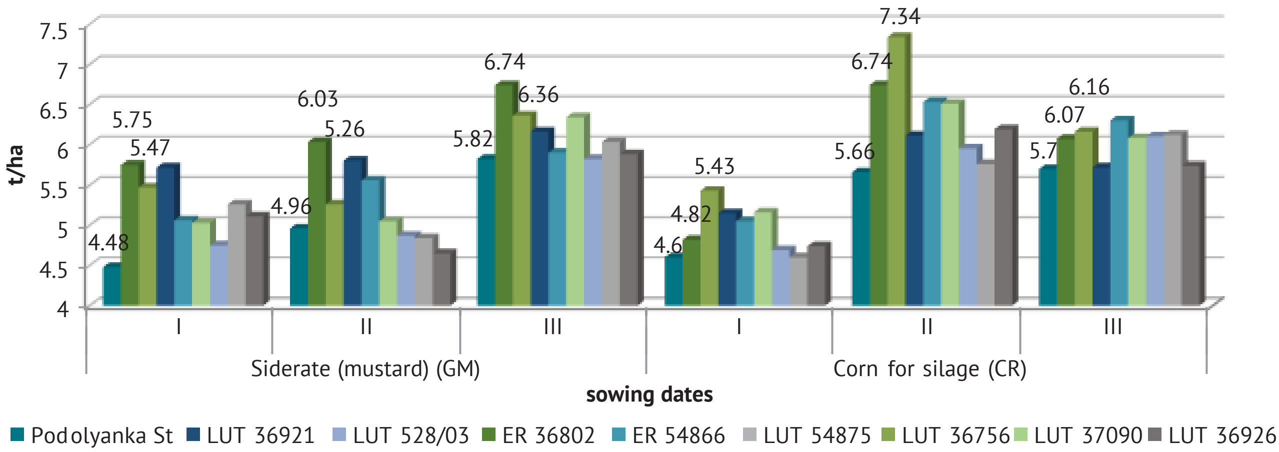

***Figure 2**. Average yield of breeding lines of soft winter wheat depending on the predecessor and sowing date, 2018-2021*

***Note:** sowing dates: I – September 15, II – September 25, III – October 5*

***Source:** compiled by the authors of this study*

The difference between the average yield values was 0.78 t/ha (GM) and 1.5 t/ha (CR) in 2018-2019; 1.83 t/ha (GM) and 1.79 t/ha (CR) in 2019-2020; 1.86 t/ha (GM) and 0.85 t/ha (CR) in 2020-2021. At the same time, the maximum level of yielding capacity in the terms of sowing dates after the preceding crops was stable: after the green manure (GM) the maximum level of average yield was for sowing at the third date (October 5), after maize for silage (CR) it was for at the second date (September 25). The ANOVA of the AMMI model confirms that in the experiment, which combined years with different weather conditions, the most part in yield variability was determined for the factor of environmental conditions (72.09%), followed in descending order by the genotype-environment interaction (25.30%), and genotype (2.61%) (Table 2).

***Table 2**. Results of AMMI model yield ANOVA for winter common wheat breeding lines, 2018-2021*

Factor	SS	Part of sum square, %	df	MS	F*
ENV	537.40	72.09	17	31.61	80.74
GEN	19.46	2.61	8	2.43	6.21
ENV*GEN	188.62	25.30	136	1.39	3.54
PC1	72.77	37.92	24	3.03	139.54
PC2	39.87	20.77	22	1.81	83.41
PC3	28.67	14.93	20	1.43	65.96
PC4	19.33	10.07	18	1.07	49.42
PC5	15.09	7.86	16	0.94	43.40
PC6	7.39	3.85	14	0.53	24.29

***Note:** ENV, environment; GEN, genotype; ENV*GEN, "genotype-environment" interaction; SS, sum square; df, degrees of freedom; MS, mean square; F, Fisher s test; PC1...PC6, principal components; *reliable at the 0.01 % level of significance*

***Source:** compiled by the authors of this study*

Environmental parameters as a background for the differentiation of breeding lines of winter wheat indicate that environmental conditions E5, E3, and E17 were the most productive (d_k = 1.16, 0.94, 0.93, accordingly), E10, E14, E7 were the least productive (d_k = -1.83, -1.70, -1.41, accordingly). In 2018-2019 in environments E1 (2019-GM$_{green\ manure}$-I$_{sowing\ date}$) and E5 (2019-CR$_{maize}$-II$_{sowing\ date}$), the highest indicators are typical for analysing backgrounds: variation of differentiating ability (σ^2DAE_k = 0.24 and 0.08, respectively); differentiating ability (σDAE = 0.49 and 0.27); relative differentiating ability (S_{ek} = 4.14 and 1.11); compensation effect (K_{ek} = 1.36 and 0.76), but they differed in terms of environmental productivity (d_k = 0.17 and 1.16) (Table 3).

***Table 3**. Environmental parameters as a background for evaluation and selection of winter wheat lines, 2018-2021*

Environment	u + d_k	Parameter of the environment						Background for assessment
		d_k	σ^2DAE_k	σDAE	S_{ek}	K_{ek}		
E1	2019-GM-I	5.77	0.17	0.24	0.49	4.14	1.36	A
E2	2019-GM-II	6.10	0.50	0.20	0.45	3.31	1.25	S
E3	2019-GM-III	6.55	0.94	0.15	0.38	2.26	1.07	L
E4	2019-CR-I	5.27	-0.33	0.05	0.23	1.01	0.64	L
E5	2019-CR-II	6.77	1.16	0.08	0.27	1.11	0.76	A
E6	2019-CR-III	6.44	0.84	0.06	0.24	0.91	0.67	S
E7	2020-GM-I	4.20	-1.41	0.24	0.49	5.68	1.36	L
E8	2020-GM-II	5.66	0.05	0.37	0.61	6.51	1.69	A
E9	2020-GM-III	6.03	0.42	0.34	0.58	5.56	1.61	S
E10	2020-CR-I	3.78	-1.83	0.23	0.48	6.09	1.33	L
E11	2020-CR-II	5.63	0.02	0.46	0.68	8.26	1.89	A
E12	2020-CR-III	5.54	-0.07	0.10	0.31	1.79	0.87	S
E13	2021-GM-I	5.56	-0.04	0.35	0.59	6.32	1.65	S
E14	2021-GM-II	3.91	-1.70	0.86	0.93	21.98	2.58	A
E15	2021-GM-III	5.48	-0.13	0.29	0.54	5.30	1.50	L
E16	2021-CR-I	5.69	0.09	0.30	0.55	5.33	1.53	S
E17	2021-CR-II	6.54	0.93	0.79	0.89	12.14	2.47	A
E18	2021-CR-III	6.01	0.40	0.25	0.50	4.14	1.39	L
Average		5.61	0.00	0.30	0.51	5.66	1.42	

***Note:** (u + dk), average yield for environment; dk, performance (impact) of environment; σ2DAEk,variance of differentiating ability of environment; σDAE, differentiating ability of environment; Sek, indicator of relative differentiating ability of environment; Kek, compensation coefficient of the kth environment; A, analysing background; S, stabilising background; L, levelling background*

***Source:** compiled by the authors of this study*

The conditions of 2019-2020 were distinguished with the lowest productivity of environments (d_k = -1.83-0.42) in the experiment. The highest differentiating ability was characteristic the environment E8 and E11 of the middle (II – 25.09) sowing dates after both preceding crops according to the indicators σ^2DAE_k (0.37 and 0.46), σDAE (0.61 and 0.68), S_{ek} (6.51 and 8.26), and K_{ek} (1.69 and 1.89). These backgrounds can be characterised as analysing ones. In 2020-2021, the environments E14 and E17 were characterized as analysing with the highest, almost at the same level, variance of differentiating ability (σ^2DAE_k = 0.86 and 0.79, respectively), differentiating ability (σDAE = 0.93 and 0.89, respectively), with strong compensation effect (K_{ek} = 2.58 and 2.47, respectively) and the maximum relative differentiating ability in the experiment (S_{ek} = 21.98 and 12.14, respectively). Of these, the first environment was low-productive (d_k = -1.70), while the second was high-productive (d_k = 0.93).

The add of multi-environmental tests in breeding process increases its effectiveness and allows singling out the most promising lines of winter common wheat based on the combination of yielding capacity and stability. The results of the analysing environments as a background for the comparison of breeding lines of winter common wheat by the level of grain yield and stability parameters indicate that there were three types of background in the experiment, namely, analysing, levelling and stabilising. The analysing background was both under favourable and stressful conditions, but the stabilising background was under conditions when breeding lines have formed the average level of productivity. The environments E1 (2019-GM-I), E5 (2019-CR-II), E8 (2020-GM-II), E11 (2020-CR-II), E14 (2021-GM-II), E17 (2021-CR-II) with the highest values of statistical parameters were characterised with the maximum destabilising effect on yield level; they ensured the contrast in genotype response and contributed to the selection of the best ones. Parametric and non-parametric statistical indicators revealed that the genotypes under study differed significantly in response to the conditions of different years. Their ranks (R) confirm the assessment of the examined parameters and allow differentiating between genotypes. The maximum general adaptive ability (GAA_{gi}) was noted in the lines G2 (0.42) and G3 (0.35) (Table 4).

***Table 4**. Characterisation and ranking of breeding lines of winter wheat according to the parameters of adaptive ability and stability for the trait of yield, 2019-2021*

Line code	GAA_{gi} – R	$\sigma^2(SAA)_{gi}$ – R	S_{gi} – R	BVG_i – R	C_{gi} – R
G1	-0.40-9	0.76-4	16.7-5	2.51-7	1.26-4
G2	0.42-1	0.85-5	15.3-4	3.18-3	1.41-5
G3	0.35-2	1.06-7	17.2-6	2.78-5	1.76-7
G4	0.14-3	0.55-2	12.9-1	3.44-1	0.92-2
G5	0.07-4	0.54-1	13.0-2	3.39-2	0.90-1
G6	0.01-5	1.09-8	18.6-8	2.39-8	1.81-8
G7	-0.19-6	0.88-6	17.3-7	2.52-6	1.46-6
G8	-0.19-7	1.10-9	19.3-9	2.17-9	1.82-9
G9	-0.20-8	0.65-3	14.9-3	2.91-4	1.08-3
Average	0.00	0.83	16.1	2.81	1.38

***Note:** GAAgi, effect of general adaptive ability; σ2(SAA)gi, dispersion (variance) of the specific adaptive ability; Sgi, %, indicator of relative stability of the ith genotype; BVGi, comprehensive indicator of breeding value of genotype; Cgi, genotype compensation coefficient; R, rank (genotype ranking)*
***Source:** compiled by the authors of this study*

The breeding line G8 was characterised with low stability at high value of the dispersion of specific adaptive ability $\sigma^2(SAA)_{gi}$ (1.10; rank 9) which was inferior to others in terms of relative stability Sg_i and breeding value of genotype BVG_i) (rank 9). The highest values of these indicators (ranks 1 and 2) were noted in G4 (0.55, 12.9, 3.44, respectively) and G5 (0.54, 13.0, 3.39). The remaining lines were unstable at high values of σ^2SAA_{gi} (>0.83, average) and compensation coefficient ($C_{gi} > 1$). The compensation coefficient close to one was noted in lines G4 and G5, therefore, when selecting for yield stability, they (lines) should be taken.

Relative stability within the average level of variability in the experiment ($Sg_i < 16.1$) was most pronounced in the lines G4 (12.9 %) and G5 (13.0 %). The lines G4, G5, and G2 with high grain yield and grain stability were better in BVG in combination with indicators GAA_{gi} and $\sigma^2(SAA)_{gi}$. With a high yield, but due to its low stability, the line G3 had an average level of breeding value ($BVG_i = 2.78$). The lines are of the most practical value if their high GAA_{gi} is combined with low yield variability under different conditions, that is, they stably form high grain yield. The lines G4, G5, and G2 best meet these criteria; the latter has high general adaptive ability, average level of yield stability and is sensitive to improving the agrotechnical conditions. According to the low indicators of coefficient of variation (CV%), the lines G4 and G2 were the most stable (15.11% and 16.50%) (Table 5).

***Table 5**. Characterisation and ranking of breeding lines of winter wheat according to parametric and non-parametric indicators of plasticity and stability*

Code	$\bar{X}$ – R	CV – R	b_i –R	S^2_{di} – R	R^2 – R	σ_i^2 – R	W_i – R	P_i – R	$S_i^{(1)}$ – R	$S_i^{(2)}$ – R
G1	5.41-7	19.31-5	1.13-4	2.07-3	0.70-5	0.38-6	5.64-7	0.89-9	0.22-1	6.01-4
G2	5.91-1	16.50-2	0.85-5	1.18-1	0.69-6	0.35-5	5.28-6	0.36-1	0.36-6	7.37-6
G3	5.73-2	18.84-4	1.49-8	6.01-7	0.79-3	0.26-3	4.12-4	0.50-3	0.22-1	5.59-3
G4	5.69-4	15.11-1	0.91-2	2.73-6	0.74-4	0.25-2	4.01-2	0.57-5	0.33-4	6.24-5
G5	5.56-5	18.21-3	1.02-1	2.39-4	0.63-7	0.46-7	6.73-8	0.57-5	0.35-5	8.82-8
G6	5.54-6	20.89-7	1.11-3	2.66-5	0.88-1	0.19-1	3.18-1	0.64-6	0.25-2	5.31-2
G7	5.40-8	19.99-5	0.75-6	1.77-2	0.79-3	0.27-4	4.18-5	0.81-7	0.25-2	5.18-1
G8	5.37-9	22.20-8	1.41-7	8.61-9	0.85-2	0.26-3	4.10-3	0.87-8	0.22-1	6.01-4
G9	5.70-3	23.41-9	0.33-9	8.24-8	0.69-6	0.70-8	9.91-9	0.40-2	0.29-3	7.82-7

***Note:** $\bar{X}$, average yield, t/ha; CV, coefficient of variation, %; bi, regression coefficient; S2di, mean square deviation from regression; R2, coefficient of determination; σi2, stability variance; Wi, ecovalence; Pi, indicator of the superiority of variety; Si(1) and Si(2), non-parametric indicators of stability; R, rank (genotype ranking)*
***Source:** compiled by the authors of this study*

According to the mean square deviation (S^2_{di}), the lines G2 and G7 were the most stable (rank 1 and 2). According to the regression coefficient (b_i), the line G5 (1.02) was characterised by the optimal response to changes in environmental conditions. The response of the line G4 (0.91) was close to optimal. The least response to change in environmental conditions was observed in the line G9 (0.33), the most response was in the line G3 (1.49). Ecovalence stability (W_i) was the highest in the lines G6 and G4 (ranks 1 and 2) and the lowest in G9 (rank 9), as for the parameter b_i. According to the indicator of the superiority of variety (P_i), the lines G2 and G9 prevailed (rank 1 and 2). The best value (rank 1) of the first non-parametric indicator of stability ($S_i^{(1)}$) was obtained by the lines G1, G3, and G8; the second non-parametric indicator of stability ($S_i^{(2)}$) was obtained by the lines G7 and G6.

Correlation analysis was used to determine the relationship between the given parameters of adaptive ability, stability, and average yield (Table 6). The indicators $\sigma^2(SAA)_{gi}$, $S_{gi,}$ $K_{gi,}$ b_i) had no significant relationship with the average yield. Selection for them can help identify stable genotypes without taking into account their yield. Above-average and average correlation was noted in the indicators S^2_{di} (r = 0.70) and BVG_i (r = 0.54), which are the most balanced for the combination of yield and stability.

***Table 6**. Correlation coefficients between the average yield of winter wheat lines and adaptability indicators, 2018-2021*

Indicator	$\bar{X}$	GAA_{gi}	$\sigma^2(SAA)_{gi}$	S_{gi}	BVG_i	C_{gi}	b_i
GAA_{gi}	**1.00**	–	–	–	–	–	–
$\sigma^2(SAA)_{gi}$	0.08	0.08	–	–	–	–	–
SAA_{gi}	0.07	0.07	**1.00**	–	–	–	–
S_{gi}	-0.28	-0.28	**0.93**	–	–	–	–
BVG_i	**0.54**	**0.54**	**-0.79**	**-0.96**	–	–	–
C_{gi}	0.08	0.08	**1.00**	**0.93**	**-0.79**	–	–
b_i	-0.13	-0.13	**0.96**	**0.97**	**-0.89**	**0.96**	–
S^2_{di}	**0.70**	**0.70**	0.19	-0.07	0.28	0.19	-0.09

***Source:** compiled by the authors of this study*

Direct correlation (+1.0) was noted between $\sigma^2(SAA)_{gi}$ and K_{gi}, and high positive correlation with S_{gi} (r = 0.93) and b_i (r = 0.96); between indicators S_{gi} and K_{gi} (r = 0.93), between S_{gi} and b_i (r = 0.97), as well as between K_{gi} and b_i (r = 0.96). A significant negative correlation was established between BVG_i and $\sigma^2(SAA)_{gi}$ (r = -0.79), S_{gi} (r = -0.96), K_{gi} (r = -0.79), and b_i (r = -0.89). All these regularities can be considered when assessing the adaptability of genotypes (breeding lines). Evaluation is an important and final stage of any breeding program before the release of a variety. At this stage, the goal is to identify lines with good results in one or more mega-environments where the lines are recommended to be grown, and to identify where the line is not recommended to be grown. At the evaluation stage, all lines must have an elite level of performance and most, if not all, of the required traits. Differences between lines are often minor compared to selection trials of early generations because phenotype and GS have improved only consistently better lines. The concept of a mega-environment is a group of environments where lines reveal themselves in the same way. B. Gerrish *et al.* (2019) note that mega-environments are usually identified using some form of cluster analysis to confirm that the environments are similar. The study by L. Crespo-Herrera *et al.* (2021) confirms that the value of knowing the mega-environment is that the breeder can select evaluation (syn. testing) sites in different mega-environments to obtain the most useful data to confirm the value of the line.

T. Begna (2022). are of the opinion that the interpretation of the performance of new varieties is impaired by genotype-environment interaction. One of the most used methods for identifying genotypes that have high and stable performance in different environments is the analysis of main effects and multiplicative interaction (AMMI). A. Seyoum *et al.* (2020), R. Kachapur *et al.* (2023), and M. Maniruzzaman *et al.* (2019) in their research confirm that variety evaluation and mega-environment identification are one of the most important tasks of environmental trials (multi-environment trial – MET) and are a prerequisite for identifying stable and high-performance genotypes. Although yield is a combined result of genotype (G), environment (E), and genotype × environment (GE) interactions, only G and GE are relevant for variety evaluation and mega-environment identification. The GGE biplot analysis graphically displays G, GE, MET in a way that facilitates visual variety assessment and mega-environment identification.

T. Asres *et al.* (2019) using ANOVA and GGE biplot evaluated twelve barley varieties, considering earliness, malt quality, grain yield and stability indicators in three districts of North Gondar (Ethiopia), which helped them to identify the high-yielding and most adapted in different environments variety IBON-174/ 03. M. Göransson *et al.* (2019) in eight regions of Northern and Central Europe evaluated 169 breeding lines of barley with respect to early maturity, height, lodging resistance under different environmental conditions. The findings showed that there are still considerable variations within the modern gene pool, and therefore the ideal combinations of alleles for regional adaptation that could facilitate the expansion of cereal cultivation further north need to be further identified. K. Van Meerbeek *et al.* (2021) noted the need for constant research on ecological stability, productivity, lodging resistance, and tolerance of created varieties to climate changes. Undoubtedly, the varieties with more consistently prominent level of productivity in combination with resistance to abiotic and biotic factors of the environment will be the most valuable for the producer.

CONCLUSIONS

The use of multi-environment (years, preceding crops, sowing dates) tests at the final stage of breeding process of winter common wheat is a practical and effective way of evaluating and selecting breeding lines (genotypes) that combine yield potential and increased stability in different weather conditions over cultivation years. The absolute yield was noted: minimum – (2.96 t/ha, G7 Lutescens 528/03), for sowing in the medium (E8, 2020-GM-II); maximum – (8.30 t/ha, G3 Lutescens 36756) – (E17, 2014-CR-II). The maximum level of yield by sowing dates after the predecessors was stable over the years: after the predecessor, sideral par (GM) had the maximum level of average yield for sowing in the third season (October 5), after maize for silage (CR) – in the second season (September 25). The inclusion of multi-environment tests in the selection process increases its effectiveness and makes it possible to single out the most promising lines of soft winter wheat based on the combination of yield and stability.

Parametric and non-parametric statistical indicators revealed that the studied genotypes differed significantly in response to the conditions of different years. Ranks (R) confirm the assessment of the studied parameters and allow to differentiate between genotypes. Selection by statistical indicators ($\sigma^2(SAA)_{gi}$, S_{gi}, K_{gi}, b_i) may help to distinguish stable genotypes without taking into account their yield. The most informative is the indicator BVG_i, which is relatively balanced in terms of productivity and stability.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Оцінка стабільності селекційних ліній пшениці м'якої озимої в багатосередовищних випробуваннях

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Анотація. Зміна клімату кидає виклик сільськогосподарському виробництву. Щоб уникнути виробничих втрат і використати потенціал, що з'являється, неминуче знадобиться адаптація в управлінні сільським господарством, зокрема шляхом створення високоадаптованих і пластичних сортів. Для отримання сортів пшениці, що поєднують продуктивність і стабільність, у 2018-2021 рр. у Миронівському інституті пшениці імені В. М. Ремесла Національної академії аграрних наук України вивчали вісім перспективних селекційних ліній пшениці м'якої озимої в багатофакторних дослідах за трьох строків сівби після двох попередніх культур. За допомогою ANOVA було встановлено, що умови середовища мали найбільший достовірний внесок у варіацію врожайності (72,09 %), взаємодія генотип-середовище та генотип мали значно менший внесок (25,30 % та 2,61 % відповідно). Строки сівби попередніх культур мали значний вплив на варіювання продуктивності лінії. Вищі врожаї були отримані після сидерату (гірчиця) у 2019 та 2020 роках. Стабільний максимальний рівень продуктивності за строками сівби був після попередника гірчиці на сидерат за сівби 5 жовтня (третій строк) та після кукурудзи на силос за сівби 25 вересня (другий строк). Встановлено, що умови другого строку сівби були аналітичним фоном для добору високоврожайних ліній озимої пшениці. Для практичної селекційної роботи відібрано селекційні лінії Lutescens 36921, Erythrospermum 36866, Erythrospermum 36802 та створено нові сорти Трудівниця миронівська, МІП Вишиванка та Грація миронівська, які характеризуються високою врожайністю та адаптивністю

Ключові слова: пшениця м'яка озима; селекційна лінія; взаємодія генотип-середовище; статистичні параметри

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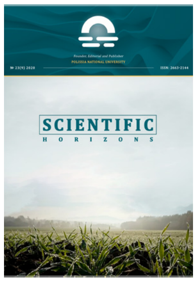

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Liquid organic-mineral fertilisers in the technology of growing winter peas

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Abstract. The issue of adapting to climate change through the expansion of crop types has sparked interest in winter peas, which can be introduced into crop rotations to stabilise the yield of legumes, positively affect soil fertility, and increase arable land productivity, but the nutrition system of winter peas needs to be investigated and

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optimised, especially considering the rising cost of mineral fertilisers. The purpose of this study was to investigate the effect of liquid organic-mineral fertilisers on the yield and quality of pea grain of winter sowing. To complete the objectives of the study, a field trial was conducted in the Odesa Oblast of Ukraine in 2021-2023. The replication of the experiment was fourfold, and the arrangement of variants was systematic. Liquid organo-mineral fertilisers were used in the experiment, which were applied once during the restoration of spring vegetation, in the budding phase and twice (restoration of spring vegetation+budding); the control variant did not involve the application of preparations. It was found that the use of liquid organo-mineral fertilisers on winter pea crops helps to increase its yield, but the growth rate is unstable, depends on weather conditions, and ranged within 0-30.4% over the years of research. The studied fertilisers had a substantial effect on the protein concentration in pea grain, the yield of which per unit area increased by an average of 22.4%, the thousand-kernel weight increased, but within the limits of statistical significance. The obtained findings suggested the possibility of using liquid organic-mineral fertilisers for growing winter peas using resource-saving or organic technology in the zone of high meteorological risks, but it should be considered that their effectiveness is determined by the composition and frequency of application. The practical value of the study lies in the development of elements of the nutrition system, which provides an increase in the yield of peas of winter sowing by 0.24-0.41 t/ha, high protein content and the level of profitability of its production – 117-152%, while the use of liquid organic-mineral fertilisers contributes to the biologisation of pea growing technology, reduces the cost of mineral fertilisers, and mitigates the chemical load on soils

Keywords: leguminous crop; weather conditions; fertilisers; productivity; grain quality

INTRODUCTION

Establishing the feasibility and effectiveness of using liquid organic-mineral fertilisers through foliar treatments of winter pea crops to ensure high yields, grain quality, and reduce the chemical load on soils determines the relevance of the study. L. Wilson *et al.* (2021) noted that the world is facing the problem of climate change and, against the background of rising average annual temperatures, changes in the spatial distribution of precipitation, the frequency of extremely high temperatures is increasing, especially in the South and South-East of Ukraine. This, as noted by N.B. Zakorcheva and Yu.S. Demidyuk (2021), requires a flexible and effective response from the agricultural sector of Ukraine to current and future variations in agrometeorological indicators through the reorientation of crops typical for the zone, optimisation of their cultivation technologies, and the introduction of new plant species and types.

The research is also stimulated by the fact that, according to H. Ferreira *et al.* (2021) and B. Carlini *et al.* (2024), the production of leguminous crops is one of the priority areas for improving protein security in the European Union, and for Ukraine, the growth of leguminous crops production means an increase in exports and strengthening the country's financial condition and economic independence. Pea (*Pisum sativum* L.) is one of the key legumes, and its grains and products are one of the main sources of protein for humans and animals (Semba *et al.*, 2021), since, unlike cereals, it accumulates up to 35% of protein, depending on the variety and growing conditions. The protein of pea grain has a high nutritional value and, as shown in the studies of S. M. Romanov and L. Storozhyk (2023), the amino acid content in winter pea grain was 21.04-21.34% or 87.7-88.9% of the total protein of 24.0%, with the share of essential amino acids prevailing.

Winter sowing of peas is of great interest to scientists and agricultural producers, as global warming has led to certain changes in the timing of the seasons: winters have become 1-3°C warmer and spring is coming earlier. V. Sichkar and R. Solomonov (2019), V. Sichkar *et al.* (2023) showed the advantages of winter sowing of peas: productive use of winter-spring soil moisture reserves, earlier maturation by 15-20 days compared to spring sowing, which makes it possible to carry out repeated sowing. Current research suggests that in the southern steppe zone, sowing is best done in the second half of October, as seedlings bearing 4-5 leaves are the most frost-resistant, and even when the weather is dry in autumn and seedlings do not emerge before the frost, the seedlings emerge together in spring and the plants develop without any deviations.

Considering the significance of peas, the Odesa State Agricultural Research Station is working to investigate and improve the nutrition system for winter peas as one of the key elements of its cultivation technology. A. Virtanen and H. Linkova (1946) reported the active use of organic amino acids by peas as a source of nitrogen, while V.P. Karpenko and Y.O. Boiko (2019) in a vegetation experiment on plants of winter peas of the NS Moroz variety showed an increase in their stress resistance to negative growing conditions when sprayed with a solution of Agroflex-Amino (1 kg/ha), which is a complex of free L-amino acids of 50% plant origin. The condition of the plants improved due to an increase in photosynthetic activity, as a week after the treatment, the content of chlorophylls increased by 24.8%, carotenoids – by 20.4%, furthermore, L-amino acids are easily available for protein synthesis.

With the establishment and growth of the market for microbial and preparations based on extracts from plants, seaweed, organic materials, as well as intra-complex compounds based on organic amino acids, fullerene or ethylenediaminetetraacetic acid (EDTA), which have stimulating properties and enhance mineral nutrition of crops, their effectiveness was also studied on pea crops and positive results were obtained. O.V. Averchev and T.S. Kovshakova (2022) found high physiological activity of the preparation "Helafit" and a mixture of boron and molybdenum when used in the phase of anthesis and budding on crops of three varieties of spring peas, which was manifested in an increase in the growing season from 4 to 6 days. According to the experiments of O.A. Kovalenko (2021), the yield of peas after treatment of seeds before sowing with Nanomix microfertiliser increased by an average of 240 kg/ha.

Trace elements have been found to affect nodule formation and nitrogen fixation: boron is required for nodule maturation; copper – for nitrogen fixation in rhizobia; iron – for several key enzymes of the nitrogenase complex, as well as for electron transfer of ferredoxin and some hydrogenases; and since molybdenum is a metal component of nitrogenase, all nitrogen-fixing systems have a specific high demand for molybdenum. When analysing the results of microfertiliser use, O.M. Vuiko (2022) emphasised that molybdenum and boron improve the nitrogen supply to pea plants and the yield increase from the application of these elements together can be 200-400 kg/ha, while copper and zinc can increase the yield by an average of 300 kg/ha.

Thus, trace elements have become a necessary component of various stimulating and nutritional preparations tested on pea crops, mostly spring peas. However, the effectiveness of fertilisers on winter pea crops is understudied, especially in terms of regulations for their use based on specific soil and climatic conditions. The purpose of this study was to establish the timing and frequency of use of liquid preparations of various origins, which include trace elements Mo, B, organic nitrogen in the form of amino acids, on pea crops of winter sowing.

MATERIALS AND METHODS

Weather conditions in the years of research. The experiments were conducted on the experimental fields of the Odesa State Agricultural Station of the Institute of Climate Oriented Agriculture of the National Academy of Agrarian Sciences of Ukraine. Odesa region is located in the Southern Steppe zone of Ukraine, which is characterised by frequent droughts, high air temperatures, and uneven distribution of rainfall. The duration and nature of weather conditions during the years of research differed significantly in terms of temperature, rainfall, and its distribution during the growth and development of winter pea plants (Fig. 1). There was a difference in the amount of precipitation and rainy days between September and full ripeness (20 June): 434 mm in 2021, 211.6 mm in 2022 and 375.5 mm in 2023, with 64, 38, and 57 rainy days, respectively (Fig. 1a).

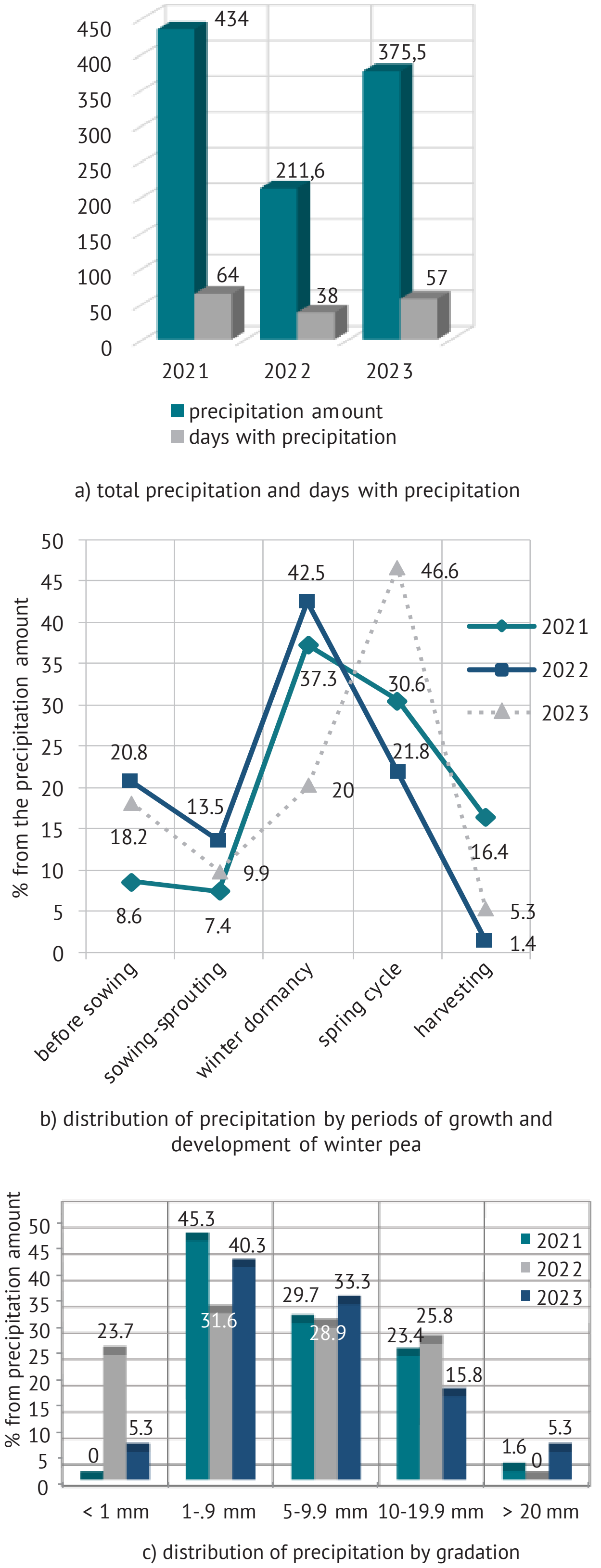

***Figure 1**. Characteristics of moisture availability in the years of research*
***Source:** data from the Odesa meteorological station of the State Emergency Service of Ukraine, systematised and processed by the authors of this study*

During the entire period of observation, both the pre-sowing period and the period from sowing to germination were insufficient in terms of rainfall. The worst year for this indicator was 2021, when precipitation was only 8.6% of the total (Fig. 1b). Winter precipitation accounted for the largest share of total precipitation in 2022 (42.5%), while in 2023 it was the smallest (20.0%). During the spring growing season, the worst year of all was 2022: during three months, the plants received only 46.1 mm of precipitation, which was only 21.8% of the total. However, in 2023, the spring moisture supply was at its highest level, with 176 mm of precipitation (46.6% of the total) from March to May, which contributed to the formation and ripening of grain.

Precipitation received by pea plants during the period of growth and development was also characterised by different quality (gradations). The year 2022 had the worst ratio of unproductive (less than 1 mm per rainfall) and low-productive precipitation (up to 5 mm): it accounted for 55.3% of the total (Fig. 1c). The air temperature in all years and throughout the growing season exceeded the climatic norm (Fig. 2), which confirms the warming trend in the study area.

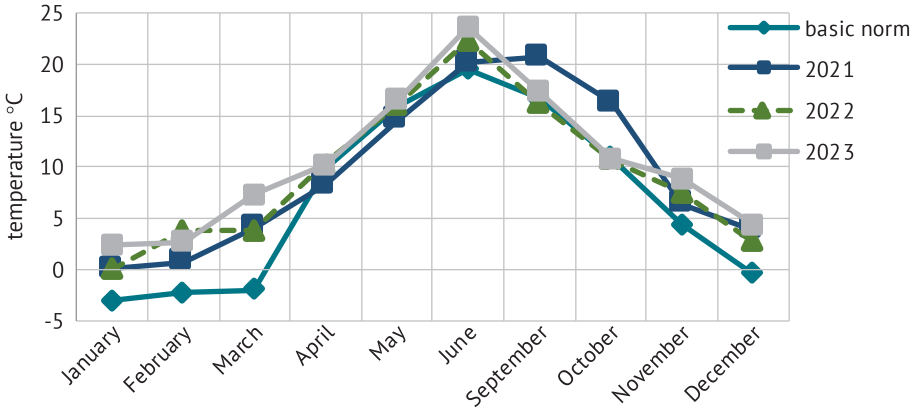

Figure 2. *Average monthly air temperature in the years of research*
Source: *data from the Odesa meteorological station of the State Emergency Service of Ukraine, systematised and processed by the authors of this study*

The soil of the experimental field is a southern low-humus heavy loamy chernozem on loess-like deposits with the following agrochemical characteristics of the arable layer: humus content – 3.71%, nitrification capacity according to Kravkov – 11.2 mg/kg; the content of available P_2O_5 and K_2O (according to Machigin) – 93.1 mg/kg and 312.8 mg/kg, respectively, which corresponds to the increased and high level of provision of these macroelements. The topsoil of the experimental field had a high content of manganese (9.74 mg/kg), cobalt (0.20 mg/kg), and copper (0.30 mg/kg), but low zinc (0.94 mg/kg) and medium molybdenum (0.09 mg/kg). The concentration of trace elements was determined in an ammonium acetate extract with a 4.8 pH, except for Mo (oxalate-buffered solution with a 3.3 pH); the content of heavy metals cadmium and lead did not exceed the maximum permissible concentrations (MPC): Cd – 0.03 mg/kg with a MPC of 2.0 mg/kg; Pb – 1.62 mg/kg with a MAC of 6.0 mg/kg (Methodology of agrochemical certification of agricultural lands..., 2019).

Liquid organo-mineral fertilisers (LOMF) produced by Tradecorp (Spain) were used in the experiment: *Tradefos B-Mo* is a fertiliser based on phosphorus (339 g/l) and potassium (319 g/l), enriched with molybdenum (7 g/l) and boron (14 g/l); *Tradebor Mo* contains boron in the form of ethanol amine (105 g/l) and molybdenum (12 g/l); *Phylgreen B-Mo* is made based on *Ascophyllum nodosum* algae extract, enriched with boron (120 g/l) and molybdenum (10 g/l); *Delfan plus* is a solution of L-£ amino acids obtained by acid hydrolysis of animal products containing 108 g/l of organic nitrogen. The scheme of the experiment is presented in Table 1.

Table 1. *Scheme of LOMF use*

Var.	Preparation	Application rate, l/ha	Development stage	
			spring vegetation recovery (SVR) (30-31)	budding (B) (51-55)
1	Control	–	–	–
2	Tradefos B-Mo	4.0	+	–
3			–	+
4			+	+
5	Tradebor Mo	2.5	+	–
6			–	+
7			+	+

Table 1. Continued

Var.	Preparation	Application rate, l/ha	Development stage	
			spring vegetation recovery (SVR) (30-31)	budding (B) (51-55)
8	Phylgreen B-Mo	2.0	+	–
9			–	+
10			+	+
11	Delfan plus	3.0	+	–
12			–	+
13			+	+

Source: *developed by the authors of this study*

The replication was fourfold, the area of the elementary plot – 20 m2, and the accounting plot – 15 m2. The experiments were designed according to the recognised methods of setting up field experiments. Soil cultivation – multi-depth, generally accepted for the rainfed conditions of the Southern Steppe. Peas of the Enduro variety were sown in the second decade of October, and the harvest was recorded in the beginning of the second decade of June. Harvesting was carried out by a Sampo-130 combine harvester (Finland) in plots with grain samples taken for analysis. The protein content of pea grains was determined by infrared spectroscopy using a Spectran-119 M (Ukraine) (DSTU 4117:2007, 2007), and the thousand-kernel weight (DSTU 4138-2002, 2004). The statistical processing of the research results was carried out using generally accepted methods in crop production (Ermantraut *et al.*, 2007; Ushkarenko *et al.*, 2008). Mathematical and statistical methods of analysis, logical and theoretical analysis were used. Experimental studies of plants (both cultivated and wild), including the collection of plant material, were performed following the institutional, national, or international guidelines. The authors of this study followed the standards of the Convention on Biological Diversity (1992) and the Convention on the Trade in Endangered Species of Wild Fauna and Flora (1979).

RESULTS AND DISCUSSION

Yield of peas of winter sowing using ROMD. Fluctuations in weather conditions over the years of research have affected the yield of winter peas. The average yield for the experimental variants by year was 3.42 t/ha in 2021, 1.31 t/ha in 2022, and 2.68 t/ha in 2023. The correlation analysis showed a very high dependence of the yield on the total moisture supply of the growing season (r = 0.94), a high dependence on the accumulation of moisture at the time of the resumption of spring vegetation (r = 0.89) and an average dependence on the amount of precipitation during the sowing – sprouting period and during the period of active spring vegetation (r = 0.62-0.66). Overall, the share of precipitation before the germination period and spring vegetation was 22.8% and 25.9%, respectively, and precipitation from the end of the growing season to the resumption of vegetation was 51.3%. The calculations showed that for every 1 mm decrease in precipitation during the growing season and in May, the grain yield of winter peas decreased by an average of 14.6 kg/ha. Precipitation in June, which occurred during the last period of grain ripening, had a weak negative impact on grain yield (r = -0.40). The increase in temperature during the entire period from the resumption of spring vegetation negatively affected the level of productivity (r =/-0.54/–/-0.89/), the greatest impact on the value of productivity was made by the average monthly temperatures of April (r = -0.79) and June (r = -0.89). In the weather conditions of 2021, the treatment of pea crops with Tradefos B-Mo solution during the renewal of vegetation did not significantly affect the crop yield compared to the control (Table 2); more effective was the treatment in the budding phase and in both phases, when the growth was 0.45 t/ha and 0.55 t/ha with $LSD_{0.95} = 0.23$.

Table 2*. Grain yield of winter peas by variants of LOMF application by years of research*

LOMF	Processing phase	Yield, t/ha				± to control			
						t/ha			
		2021	2022	2023	mean	2021	2022	2023	mean
Control	–	3.05	1.23	2.27	2.18	–	–	–	–
Delfan plus	VVV*	3.40	1.23	2.64	2.42	0.35	0	0.37	0.24
	B**	3.54	1.33	2.92	2.60	0.49	0.10	0.65	0.41
	SVR+B***	3.68	1.38	2.70	2.59	0.63	0.15	0.43	0.40
Tradefos BMo	SVR	3.24	1.42	2.58	2.41	0.19	0.19	0.31	0.23
	B	3.50	1.31	2.68	2.50	0.45	0.08	0.41	0.31
	SVR+B	3.60	1.35	2.51	2.49	0.55	0.12	0.24	0.30
Tradebor Mo	SVR	3.72	1.31	2.43	2.49	0.67	0.08	0.16	0.30
	B	3.23	1.28	2.61	2.37	0.18	0.05	0.34	0.19
	SVR+B	3.53	1.42	2.48	2.48	0.48	0.19	0.21	0.30

Table 2. Continued

LOMF	Processing phase	Yield, t/ha				± to control t/ha			
		2021	2022	2023	mean	2021	2022	2023	mean
Phylgreen BMo	SVR	3.28	1.23	2.84	2.45	0.23	0	0.57	0.27
	B	3.35	1.24	2.96	2.52	0.30	0.01	0.69	0.34
	SVR+B	3.38	1.26	2.80	2.48	0.33	0.03	0.53	0.30
$LSD_{0.95}$		0.23	0.04	0.15		0.23	0.04	0.15	

Notes: ** – spring vegetation recovery; ** – budding; *** – spring vegetation recovery + budding Phases of foliar fertilisation – * spring vegetation recovery; ** – budding; *** – spring vegetation recovery + budding*
Source: *compiled by the authors of this study based on conducted research*

The use of Tradebor Mo was significantly effective at an earlier stage of pea plant development, with a yield increase of 22.0% or 0.67 t/ha; the preparation based on seaweed extract (Phylgreen B-Mo) provided small increases from 0.23 t/ha to 0.33 t/ha, depending on the timing and frequency of treatment. The twofold treatment with Delfan plus increased the yield of winter peas by 0.63 t/ha (20.6%). In 2022, organo-mineral fertilisers enriched with boron and molybdenum (Tradefos BMo Tradebor Mo) gave the same growth (15.4%), but at different stages of development of winter peas: Tradefos BMo, which, apart from trace elements, contains soluble forms of phosphorus and potassium, provided such an increase when fertilising at the stage of spring vegetation renewal, while Tradebor Mo – when fertilising vegetative plants twice (VSR+budding)

In the dry conditions of 2022, there was no significant effect of treating crops with a solution of organic amino acids (Delfan plus) during vegetation recovery, while the use of an algae-based preparation (Phylgreen BMo) in these weather conditions did not generally result in a significant increase in pea yields. In the more favourable year of 2023, the increase from spraying with Phylgreen BMo solution was 0.53-0.69 t/ha ($LSD_{0.95}$ = 0.15 t/ha) or 23.3-30.4%; on average, over three years, the maximum effect was obtained when using this preparation in the budding phase and when double spraying (VSR+budding), when the increase in winter pea yield was 15.6% and 13.8% or 0.34 t/ha and 0.30 t/ha.

In 2023, Tradefos BMo and Tradebor Mo organo-mineral fertilisers provided the maximum growth (18.1% and 15.0%) when used during the budding phase. On average, over three years, Tradefos BMo provided the maximum increase in pea yields when treating crops in the budding phase (14.2%), while Tradebor Mo when used at the time of pea vegetation recovery – 11.8%, and 13.8% when applied twice. Thus, there is instability in the effectiveness of the LOMF in time and space. However, based on the findings of three years of research (Fig. 3), it is possible to determine the best time for treating winter pea crops with LOMF solutions.

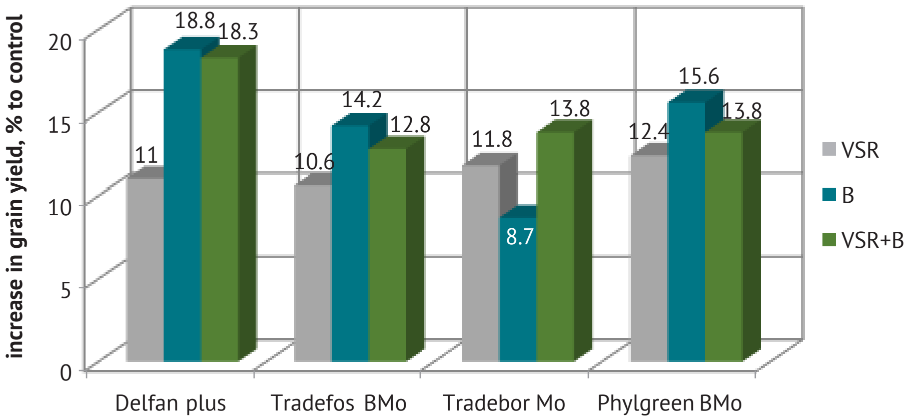

Figure 3. *Average yield increases of winter peas using LOMF over the years of research*
Source: *compiled by the authors of this study based on conducted research*

All the studied LOMFs (except Tradebor Mo) contributed to the maximum increase in the yield of peas of winter sowing when used in the budding phase, the increase ranged within 14.2-18.8%. Delfan plus (+18.8%) stands out among the preparations in terms of effectiveness. According to the level of impact on yield, the LOMFs are ranked as follows: Delfan plus > Phylgreen BMo > Tradefos BMo > Tradebor Mo. The findings obtained are confirmed in the studies of other researchers. Many studies report an increase in the yield of various crops by 10-25% under the influence of preparations containing trace elements. For instance, in the experiments of M.V. Kapinos (2020), conducted in the Southern Steppe of Ukraine, the increase in the yield of three pea varieties with pre-sowing seed treatment with such preparations ranged within 14.9-15.2%.

According to the conclusions of S. Skok *et al.* (2023), the effectiveness of the use of micronutrient preparations depends on the crop, its developmental stage, and the frequency of treatment: when peas, winter wheat, sunflower were treated twice with Nano-Agro solution in the early stages of development (before flowering), yield increases ranged within 12.0-16.0%, and a single treatment after flowering was 4.0%. According to the findings of M. Janmohammadi *et al.* (2023), obtained in the arid conditions of northwestern Iran, the introduction of trace elements by foliar spraying of wheat crops increased the yield within 10-14%, and in combination with pre-sowing seed treatment and the use of biological products – up to 21.0%. However, the researchers do not analyse the stability of such factors depending on weather conditions, elements of technology, and the level of soil fertility.

Quality of winter pea grain. The main quality indicators of commercial peas are grain protein content and grain size (thousand-kernel weight). Within each year of research, the protein content in pea grain of the experimental variants substantially exceeded that of the control (Table 3).

***Table 3**. Protein content in winter pea grain and its yield from 1 ha of sowing by experimental variants*

Experiment variant	Processing phase	Protein, %			Protein, kg/ha				
		2021	2022	2023	2021	2022	2023	mean	± to control
control	–	18.63	21.76	20.85	568.2	267.2	473.2	436.2	–
Delfan plus	SVR	19.48	23.48	22.53	662.3	288.2	594.9	515.1	78.9
	B	20.12	22.71	22.75	712.1	303.1	664.1	559.8	123.6
	SVR+B	20.20	22.69	22.80	743.4	312.0	615.6	557.0	120.8
Tradefos BMo	SVR	19.23	23.05	23.15	623.0	327.0	597.2	515.7	79.5
	B	19.52	22.91	22.97	683.2	300.5	615.6	533.1	96.9
	SVR+B	20.07	23.39	23.18	722.5	315.7	581.8	540.0	103.8
Tradebor Mo	SVR	19.28	22.61	22.56	717.2	296.8	548.1	520.7	84.5
	B	19.89	23.58	23.07	642.4	302.1	602.0	515.5	79.3
	SVR+B	20.01	22.48	23.27	706.4	318.6	577.1	534.0	97.8
Phylgreen BMo	SVR	19.25	22.52	21.42	631.4	277.7	608.3	505.8	69.6
	B	19.86	22.68	22.00	665.3	280.9	651.1	532.4	96.2
	SVR+B	20.15	22.03	22.70	681.1	277.8	635.6	531.5	95.3
LSD_{095}		0.56	0.60	0.75	–	–	–	–	–

***Notes:** * – spring vegetation recovery; ** – budding; *** – spring vegetation recovery + budding*
***Source:** compiled by the authors of this study based on conducted research*

Under the conditions of drought in 2022, there was no significant dependence of pea protein content on the term and frequency of treatment, but under conditions of relatively better moisture availability (2021 and 2023), a significant increase in protein content was observed when fertilising crops during the budding phase and at two times. On average, over three years, the maximum increase in grain protein content relative to the control variant was observed when using Tradebor Mo in the budding phase (8.7%) and Tradefos BMo (+8.8%) with two fertilisations (Fig. 4); the minimum increase compared to other preparations was observed in the Phylgreen BMo variants: from 3.2% to 6.0%.

The protein yield per unit area was determined by the yield and concentration of the product in the grain, and its value in the experimental plots significantly exceeded the control both for each of the years of research and on average (Table 3, Fig. 5).

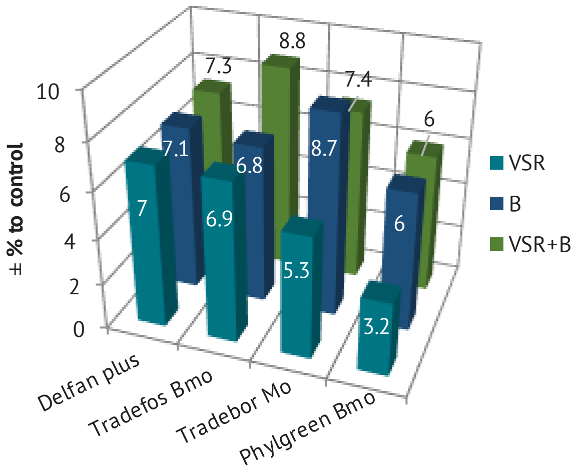

***Figure 4**. Increase in protein concentration in winter pea grain relative to control*
***Source:** compiled by the authors of this study based on conducted research*

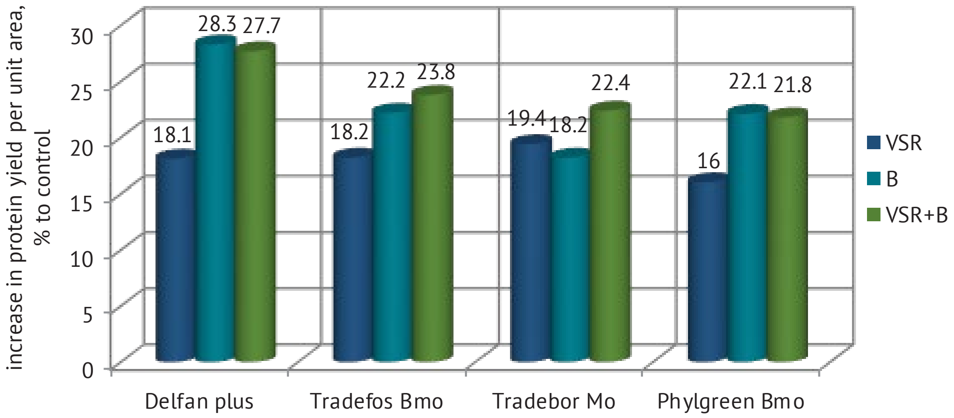

***Figure 5**. Increase in protein yield per unit area of winter sown peas relative to the control*
***Source:** compiled by the authors of this study based on conducted research*

Notably, the percentage of increase in protein yield when feeding during the budding phase and under conditions of double spraying have very close values within one preparation in three cases out of four: Delfan plus – 27.7-28.3%; Tradefos BMo – 22.3-23.8%; Phylgreen BMo – 22.1-21.8%. Double feeding of winter pea crops with Tradebor Mo solution leads to an increase in protein yield by 22.4%, while with single treatments – 19.4-18.2%. The effect of organo-mineral preparations on the thousand-kernel weight of pea grains is positive: in all years and in all variants there is a tendency to improve the size (Table 4).

***Table 4**. Thousand-kernel weight of wintering peas by variants of LOMF fertilisation*

Experiment variant	Processing phase	Thousand-kernel weight, g				± to control
		2021	2022	2023	avg	gram
control	–	164.2	181.7	184.7	176.9	–
Delfan plus	SVR	183.4	182.1	185.6	183.7	6.8
	B	185.3	178.7	180.1	181.4	4.5
	SVR+B	186.3	185.8	186.1	186.1	9.2
Tradefos BMo	SVR	186.2	181.9	183.9	184.0	7.1
	B	176.9	181.5	184.0	180.8	3.9
	SVR+B	182.3	183.7	188.4	184.8	7.9
Tradebor Mo	SVR	178.6	184.1	186.2	183.0	6.1
	B	176.3	183.6	182.2	180.7	3.8
	SVR+B	180.4	183.0	184.0	182.5	5.6
Phylgreen BMo	SVR	172.2	180.4	184.3	179.0	2.1
	B	174.3	182.6	183.8	180.2	3.3
	SVR+B	175.2	180.4	187.0	180.9	4.0
LSD_{095}		7.9	3.8	4.2	–	

***Notes:** * – spring vegetation recovery; ** – budding; *** – spring vegetation recovery + budding*
***Source:** compiled by the authors of this study based on conducted research*

Only in 2021, the thousand-kernel weight was significantly higher (8.0-22.1 g) than the control variant at LSD_{095} = 7.9 grams. On average, over three years, the increase in the thousand-kernel weight did not exceed the level of 5% error (Fig. 6). However, polynomial trend lines (second degree) within each of the studied preparations showed a high probability of increasing the thousand-kernel weight when switching from a single feeding during the period of vegetation recovery to a double feeding (SVR+budding), as evidenced by the approximation coefficients at the level of 0.95-0.99. The results obtained suggest the significance of the frequency of fertilisation in the cultivation of winter peas, which was confirmed in the experiments of V.V. Shevchuk (2023) in the conditions of the Vinnytsia Oblast on two winter pea varieties NS Moroz and Enduro, where a combination of pre-sowing seed treatment with biological preparations, post-sowing application of $N_{45}P_{45}K_{45}$ and two-time foliar feeding with microfertilisers (3-5 leaves and budding) promoted growth plant mass, depending on the microfertiliser options, ranges within 15-66%, and when using one top dressing – within 12-46%.

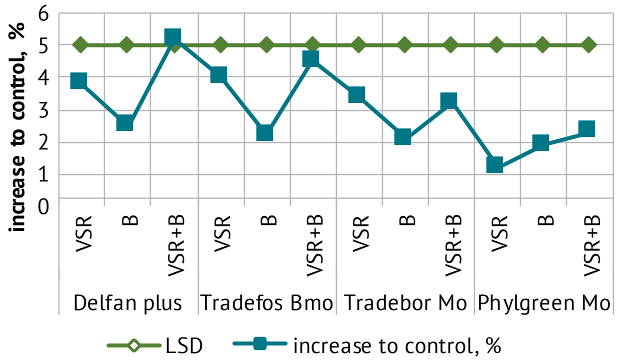

Figure 6*. Increase in thousand-kernel weight compared to the control variant*
Source: *compiled by the authors of this study based on conducted research*

Most of the observations on the impact of fertilisers on grain yield and quality were made in studies with spring peas and confirm the hypothesis that these indicators, even for a legume, depend on improved mineral nutrition, including nitrogen, and the degree of impact can be determined by the type of fertiliser, timing of application, and doses, but there is a positive effect in most cases. With equal doses of nitrogen from different sources: mineral fertilisers, cattle manure, and sheep manure (Karadaş & Ceyhan, 2023), the increase in the thousand-kernel weight of peas compared to the control without fertiliser was 13.4%, 5.5%, and 5.2%, while the protein concentration was 0.7%, 1.7%, and 2.9%, respectively.

L. Yeremko *et al.* (2024) noted the advantage of fractional application of nitrogen over one-time application and the combination of post-sowing application $N_{30}P_{45}K_{45}$ with feeding N_{15} in BBCH 22–23, which made it possible to increase thousand-kernel weight, yield, protein content, and total protein yield by 26.2%, 11.1%, and 43.5%, respectively, compared to the control. The use of chelated micronutrient fertilisers in combination with liquid biofertilisers increased the availability of nutrients and contributed to an increase in the thousand-kernel weight and protein content in pea grains (Sayed & Ouis, 2024), which is not in contradiction with the findings of the presented study. On the infertile sandy soils of Egypt, A.E.M. Eata *et al.* (2020) studied the effectiveness of foliar spraying with Agua Cool against the background of organic (compost at a rate of 2.5 t/ha) and mineral nitrogen (ammonium sulphate – 243 kg/ha); in the first case, the protein concentration in pea grain increased by an average of 8.2%, while the thousand-kernel weight – by 9.6% compared to the control without fertiliser, and against the background of mineral nitrogen – by 9.0% and 24.1%.

In the presented studies, the drug Delfan plus was used, which is a solution of L-£ amino acids obtained by acid hydrolysis of animal products. K. Dinkeloo *et al.* (2020) found that amino acids have an advantage over other nitrogen sources due to their mobility and easy transport in plants and therefore directly or indirectly affect plant growth, yield, and product quality. Admittedly, Delfan plus, when introduced into pea cultivation technology, increased grain yield from 11.1% to 18.8%, while protein content increased from 7.0% to 7.3% compared to the control (Fig. 4). The positive effect of the amino acid when using an acidic biostimulant identical in composition to Delfan plus was found in the experiments of W. Biel *et al.* (2023), where the yield of pea seeds increased by 13.0%, while the protein concentration in peas increased by 2.1 absolute percent or 9.4% relative to the control variant, which is also consistent with the data presented by Y. Mohammed *et al.* (2018) and S. Daba *et al.* (2022).

However, there are also results that point to the greater importance of factors other than fertilisers. Thus, in Poland, a long-term experiment using nitrogen isotopes (Faligowska *et al.*, 2022) showed that nitrogen accumulated in pea seeds from three sources: the atmosphere (average value 35.2%), fertilisers (6.8%), and soil (57.9%), which was 48.6%, 9.9%, and 85.4 kg/ha, respectively. On three pea varieties, D. Janusauskaite (2023) studied the effectiveness of nitrogen application in the norm from 0 to 60 kg/ha against the background of $P_{40}K_{80}$ and showed that the protein concentration in the grain had a greater influence on precipitation during the growing season (48.6-52.6%), while the combined effect of weather conditions and nitrogen fertilisers was within 1.1-2.2% of the total variance of protein content; therewith, the protein concentration in pea grains of fertiliser variants decreased by an average of 2.6% relative to the control without fertilisers, and increasing the dose of mineral nitrogen reliably reduced the thousand-kernel weight by 2.7-3.5%.

However, from the standpoint of scientific development, both positive and negative and complex results do not contradict each other but complement and expand knowledge and contribute to the development of more sound elements of crop cultivation technology, considering climate change, varietal characteristics, soil condition, and type.

CONCLUSIONS

Liquid organo-mineral fertilisers: Delfan plus, Phylgreen BMo, Tradefos BMo, Tradebor Mo show effectiveness on pea crops sown in winter, but it is not stable in terms of the impact on yields and depends on weather conditions and the type of preparation: yield increases over the years of research ranged within 0-30.4%. The level of winter pea grain yield was greatly influenced by precipitation during the growing season: paired correlation coefficients showed a very high dependence on the amount of precipitation during the entire period of plant growth and development (r = 0.94), a high dependence on moisture accumulation at the time of spring vegetation resumption (r = 0.89), and an average dependence on the amount of precipitation during the pre-germination and active spring vegetation period (r = 0.62-0.66), and the share of precipitation influence from the cessation to the resumption of vegetation was 51.3%. For each 1 mm decrease in precipitation, the yield decreased by an average of 14.6 kg/ha over the growing season. Precipitation during the grain ripening period had a weak negative effect on grain yield (r = -0.40). The increase in temperature during the entire period from the resumption of spring vegetation negatively affected the level of productivity (r = /-0.54/–/-0.89/), the greatest impact on the value of productivity was made by the average monthly temperatures of April (r = -0.79) and June (r = -0.89).

Based on three years of research, the following can be distinguished: Tradefos BMo (4 l/ha) and Phylgreen BMo (2.0 l/ha) are best used in the budding phase of winter peas, which ensures an increase in yield by 13.1% and 15.6%, and Tradebor Mo (2.5 l/ha) – during the spring vegetation recovery period (+11.8%), if a second treatment is carried out during budding, the yield increase will be 12.4%. All the tested preparations had a significant effect on both the absolute protein content of pea grain and its yield per sown area, with the latter increasing within 14.1-30.6%. The effect of liquid organo-mineral fertilisers on the thousand-kernel weight was positive but fluctuated mostly within the limits of reliability.

Calculations based on the results of research with liquid organo-mineral fertilisers enriched with trace elements boron and molybdenum and organic amino acids showed that fertilising pea crops for winter sowing with their solutions makes it possible to obtain additional profit in the amount of 1.52-2.81 g for each UAH spent (in conditions of severe drought – 0.35 UAH/kg). These findings were obtained at a high level of availability of available forms of nitrogen and phosphorus in southern black soil and a prominent level of potassium. Winter sowing of peas is considered a promising technique in the context of climate change in the Southern Steppe, and therefore it is worth investigating the effectiveness of liquid organic-mineral fertilisers depending on the level of soil fertility and their use in combination with other elements of technology, such as sowing dates and pre-sowing seed treatment.

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None.

CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Рідкі органо-мінеральні добрива в технології вирощування гороху зимуючого

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Анотація. Питання пристосування до кліматичних змін через розширення видів сільськогосподарських культур викликало інтерес до гороху зимуючого, введення якого в сівозміни дасть можливість стабілізувати врожайність зернобобової культури, позитивно вплинути на родючість ґрунту та підвищити продуктивність ріллі, але система живлення гороху підзимової сівби потребує вивчення та оптимізації, особливо з огляду на тенденції зростання вартості мінеральних добрив. Метою представлених матеріалів було дослідження впливу рідких органо-мінеральних добрив на врожай та якість зерна гороху підзимової сівби. Для реалізації поставлених завдань був виконаний польовий дослід в умовах Одеської області у період 2021-2023 рр. Повторність в досліді чотирьох кратна, розташування варіантів – систематичне. В досліді використано рідкі органо-мінеральні добрива, які вносили одноразово при відновленні весняної вегетації, у фазу бутонізації та двічі (відновлення весняної вегетації+бутонізація); контрольний варіант не передбачав внесення препаратів. Встановлено, що застосування рідких органо-мінеральних добрив на посівах гороху зимуючого сприяє підвищенню його врожайності, але величина зростання не стабільна, залежить від погодних умов і за роками досліджень коливалася від 0 % до 30,4 %. Досліджувані удобрювальні речовини мали суттєвий вплив на концентрацію білка в зерні гороху, вихід якого з одиниці площі зростав в середньому на 22,4 %, маса 1000 насінин збільшувалася, але в межах достовірності. Отримані результати вказували на можливість використання рідких органо-мінеральних добрив при вирощуванні гороху зимуючого за ресурсоощадною чи органічною технологією в зоні високого ступеня метеорологічних ризиків, але слід враховувати, що їх ефективність визначається складом иа кратністю внесення. Практична цінність дослідження полягає у розробленні елементів системи живлення, яка забезпечує підвищення врожайності гороху підзимової сівби на 0,24-0,41 т/га високий вміст білка і рівень рентабельності його виробництва – 117-152 %, а використання рідких органо-мінеральних добрив сприяють біологізації технології вирощування гороху, скороченню витрат на мінеральні добрива да зниженню хімічного навантаження на ґрунти

Ключові слова: зернобобова культура; погодні умови; удобрювальні речовини; продуктивність; якість зерна

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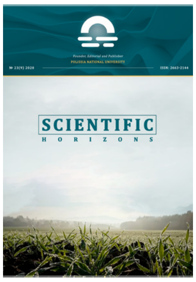

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Evaluation of barley plants growth and development at the beginning of tillering phenophase at different sowing dates

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Abstract. Global climate change, which has also occurred in the Western Forest-Steppe of Ukraine, has led to early sowing starting from the very beginning of the spring season. In this regard, to provide a scientific basis for spring barley cultivation technology, the issue of investigating the processes of plant growth and development before the onset of the tillering phenomenon, i.e., the second and third stages of organogenesis, is of particular relevance. The purpose of this study was to

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establish the regularities of dependence of spring barley plant growth and development on the influence of vegetation factors at different sowing dates in the Western Forest-Steppe of Ukraine. To summarise the findings, the following methods were employed: general scientific methods based on objectivity, evidence, reproduction, and mathematical and statistical methods for processing experimental data. The study found the dependence of the processes of growth and development of spring barley plants based on plant biomass, crude biomass, and dry matter content of the root system and aerial parts of plants, as well as leaf area according to the analysis at the beginning of the tillering phase, on the influence of sowing time. The study estimated the significance of the studied factor under the influence of supply conditions for the maximum realisation of spring barley productivity potential. As a result, a regularity was revealed, according to which a substantial decrease in the productivity potential of barley plants was established with a delay for each subsequent 10 days starting from the first sowing date on 10 March. The maximum data values were obtained at the first sowing date, where the plant biomass was 723.6 mg, the crude biomass of the root system was 67.5 mg, the dry matter of the root system was 18.0 mg, the crude biomass of the aerial part of the plant was 656.1 mg, the dry matter of the aerial part of the plant was 130.8 mg and the leaf surface area was 18.1 cm^2. As a result of the scientific substantiation, the practical value of the study lies in the favourability of early sowing dates to ensure maximum realisation of plant productivity potential due to vegetation factors

Keywords: plant biomass; crude biomass; dry matter; root system; aerial part of plants; leaf surface area; Student's t-test

INTRODUCTION

The issues of growth and development of spring barley plants at early sowing dates are insufficiently covered and understudied, which became the basis for conducting relevant research. In this regard, it is important to develop new approaches and improve the existing elements of crop cultivation technology that can ensure maximum fulfilment of the biological potential under the existing soil and climatic conditions as a result of changes in the soil and climate. Therefore, with climate change and improved agricultural technology, optimising barley sowing dates is becoming increasingly important.

Barley (*Hordeum vulgare* L.) is one of the most widely grown cereals and ranks fourth in the world in terms of production. Barley grain is widely used not only for food, technical and feed purposes, but also for brewing (Bratković *et al.*, 2024). Improving existing and developing new technologies for growing grain crops, including spring barley, has always been an important area of agricultural production. That is why one of the ways to increase barley grain yields is to create favourable conditions for the fulfilment of plant productivity potential. As a rule, the sustainable development of agricultural production of grain crops, including spring barley, largely depends on climatic conditions, which are determined by the ratio of heat, moisture, and light. They are one of the determining factors of plant life, which affect not only their growth and development, but also productivity in general (Shelkoplyas & Zhytkov, 2021; Balabukh *et al.*, 2021). Climate change, which has been observed over the past decades, is affecting the growth, development, and yield of crops.

M. Zulkiffal *et al.* (2021) noted that the main abiotic factors limiting global cereal production are drought and rising air temperatures. It is the presence of such conditions that leads to a 10-50% reduction in grain yields. This problem is also relevant for Ukraine. V. Balabukh (2023) believes that further changes in climate conditions are projected, associated with an increase in the number of extreme events such as heat, drought, and heavy rainfall. This will negatively affect the growth and development of crop plants. As a result of high air temperatures, the dates of onset of phenological phases and the duration of grain growth periods have shifted. Sowing dates should be shifted to reduce the impact of extreme conditions (Fatima *et al.*, 2020).

K. van der Wiel and R. Bintanja (2021), M. Appiah *et al.* (2023) describe that early sowing compared to late sowing increases the rate of photosynthesis, seed assimilates and germination activity. Late sowing substantially reduces barley grain yields. For the formation of yield and grain quality of spring barley, the tillering period is crucial – the emergence of the tube, when functional shoots and elements of ear productivity are laid down – important components of the future harvest. At low temperatures, the duration of the tillering period is extended, which leads to the development of more lateral shoots in plants. Since the dynamics of tillering is also influenced by the length of daylight hours, the conditions depending on the sowing date become a factor influencing the tillering processes and the number of shoots per unit area. High yields and good grain quality of barley will be achieved if the "inputs" are directed to plant development at the beginning of the growing season. There are a series of conditions for plant growth and development to achieve high yields and grain quality. At the beginning of the first stage of plant development, the main vegetative phase, phyllochrons, roots, and shoots are formed. The agronomic importance of this stage lies in the formation of sufficient biomass.

The ability to form leaves and productive shoots is a significant component of plant biomass accumulation during the vegetative growth phenophase. Leaf area is considered an indicator of plant growth and development and is closely related to leaf weight. These are the main factors that influence growth rate through leaf thickness and density (Panfilova *et al.*, 2019a). Leaf area is a significant parameter for assessing intrinsic plant processes, such as photosynthesis and transpiration. Photosynthesis is known to be the main source of dry matter and crop yields. Aboveground mass plays a significant role in plant life, as it mobilises carbohydrates and nitrogen-containing substances to form the productive part of the crop. During the process of photosynthesis, energy-rich substances and organic compounds of various chemical compositions are formed from simple substances (Panfilova *et al.*, 2019b). As a rule, the intensity of organic matter accumulation depends on the size of the leaf surface.

Considering the above, the purpose of this study was to establish the regularities of the influence of conditions at different sowing dates in the Western Forest-Steppe of Ukraine on the results of growth and development of spring barley plants at the beginning of the tillering phase to effectively fulfil the productivity potential of the crop.

MATERIALS AND METHODS

The field experiment was organised by laying out plots in 4 replications with a plot area of 20 m^2. Sowing dates: first – 10 March, second – 20 March, third – 30 March, fourth – 9 April, fifth – 19 April. The object of study is spring barley plants of the Sebastian variety. The seeding rate is 250 germinating seeds/m^2. The soil temperature was set according to the data from the Pessl Instruments iMetos IMT300USW weather station (Austria). The study was conducted during 2018-2020 at the Higher Education Institution "Podilskyi State University" in the Western Forest-Steppe of Ukraine.

Agrochemical characteristics of the soil of the experimental plots. The soil type is podzolised gleyey medium loamy chernozem, which is characterised by physical and agrochemical properties as favourable for growing crops. Humus content is 3.2%, provision of nutrients: alkaline hydrolyzed nitrogen – 100 mg per 1 kg of soil, mobile phosphorus P_2O_5 – 176 mg per 1 kg of soil, exchangeable potassium K_2O – 160 mg per 1 kg of soil. The reaction of the soil solution is close to neutral or neutral – the pH of the salt extract is 6.8-7.0 mg-eq/100 g of soil, the hydrolytic acidity is low – 0.56-0.62 mg-eq/100 g of soil, the amount of absorbed bases is 32-36 mg-eq/100 g of soil.

The content of humus was determined according to the Tyurin method, alkaline-hydrolysed nitrogen – by the Cornfield method, mobile phosphorus and exchangeable potassium – by the Chirikov method, the sum of absorbed bases by the Kappen-Hilkowitz method, the reaction of the soil solution pH salt – by the potentiometric method, and hydrolytic acidity – by the Kappen method. The experiment was organised under the condition of forming crops with a row spacing of 15 cm – a conventional row seeding method. Sowing depth was within 2-3 cm. The grain weight of barley seeds used for sowing was 48-52 mg. Leaf surface area was determined by the notching method, crude plant biomass – by weighing on the FEH-600L balance (Ukraine), and dry matter mass by the thermogravimetric method (Hrytsaenko *et al.*, 2003; Yeshchenko *et al.*, 2014). For the mathematical analysis of the obtained findings, the Student's t-test was used to determine the dependence of spring barley plant biomass, crude biomass and dry matter content of the root system and aerial parts of plants, as well as leaf area on sowing dates. Experimental studies of plants (both cultivated and wild), including the collection of plant material, were following the institutional, national, or international guidelines. The study adhered to the standards of the Convention on Biological Diversity (1992) and the Convention on Trade in Endangered Species of Wild Fauna and Flora (1979).

RESULTS AND DISCUSSION

The climate has been warming over the past two decades. In this regard, the issue of analysing early cereal crops in terms of growth and development at the beginning of the tillering phenomenon depending on different sowing dates is relevant. At the first sowing date of 10 March, the biomass of the barley plant at the beginning of tillering was 722.3 mg. In the second sowing term, the same indicator was characterised by a lower value of 593.5 mg, the difference of 128.8 mg was significant, Student's criterion t_f – 16.97 > $t_{0.05}$ – 2.01. At the third sowing date, the plant biomass index was 538.1 mg, which is 55.4 mg less than the data obtained at the second sowing date. The difference is significant at t_f – 6.70 > $t_{0.05}$ – 2.01. At the fourth sowing date, the plant biomass was significantly lower than at the third sowing date by 56.1 mg (t_f – 6.56 > $t_{0.05}$ – 2.01). At the fifth sowing date, the plant biomass was the lowest and amounted to 433.9 mg, the difference when compared to the data of the fourth sowing date of 48.1 mg was significant (t_f – 5.58 > $t_{0.05}$ – 2.01). The obtained findings of spring barley plant biomass, crude biomass, and dry matter content of the root system and aerial parts of plants, as well as leaf area at different sowing dates in 2018 are presented in Table 1.

***Table 1**. Characteristics of the growth and development of barley plants at the beginning of the tillering phenophase at different sowing dates (2018)*

Sowing period	Plant biomass, mg	Root system, mg		Aerial part, mg		Leaf area, cm^2
		raw biomass	dry matter	raw biomass	dry matter	
1	722.3 ± 4.9	67.3 ± 2.2	18.0 ± 0.50	655.0 ± 7.0	130.7 ± 3.7	17.9 ± 0.48
2	593.5 ± 5.8	44.5 ± 2.8	13.2 ± 0.61	549.0 ± 6.3	97.0 ± 2.3	15.6 ± 0.35
3	538.1 ± 5.9	31.5 ± 3.3	10.3 ± 0.70	506.6 ± 5.8	83.3 ± 1.9	14.2 ± 0.41
4	482.0 ± 6.2	19.7 ± 2.2	7.5 ± 0.52	462.3 ± 6.0	71.7 ± 2.6	12.9 ± 0.33
5	433.9 ± 6.0	12.2 ± 1.7	5.3 ± 0.49	421.7 ± 6.5	63.0 ± 1.8	11.0 ± 0.31

***Source:** developed by the authors*

The weight of the crude biomass of the root system of barley plants at the first sowing date was 67.3 mg, while at the second – 44.5 mg. The difference in the comparison of the 22.8 mg data is significant, Student's criterion t_f is 6.40 > $t_{0.05}$ – 2.01. When sowing in the third term, the same indicator of plants was even lower – 31.5 mg, the difference of 13.0 mg compared to the data of the second term is significant (t_f – 3.00 > $t_{0.05}$ – 2.01). At the fourth sowing term, the crude biomass of the root system was 19.7 mg, which is 11.8 mg less than the same indicator of the third term plants (t_f – 2.98 > $t_{0.05}$ – 2.01). The difference between the data of the fourth and fifth sowing periods of 7.5 mg was significant, which proves that the parameters of the indicator are much lower when sowing in the fifth period. The difference between the obtained data on the content of dry matter of the root system of spring barley plants in the comparison of the first and second sowing periods was 4.8 mg and was significant due to the reduced values in the second period (t_f – 6.15 > $t_{0.05}$ – 2.01). When sowing in the third term, the weight of the root system dry matter was 10.3 mg, which is significantly less than the data of the second sowing term by 2.9 mg (t_f – 3.15 > $t_{0.05}$ – 2.01). For sowing in the fourth term, the figure was 7.5 mg, which is significantly less than in the third term by 2.8 mg (t_f – 3.22 > $t_{0.05}$ – 2.01). And at the fifth sowing term, the dry weight of the root system was 5.3 mg and was significantly less by 2.2 mg compared to the data for the fourth term, Student's criterion t_f – 3.10 > $t_{0.05}$ – 2.0.

Analysis of the above-ground plant data in terms of crude biomass also proves that when the sowing date is shifted from 10 March to every 10 days thereafter, plant biomass significantly decreases. Specifically, the biomass in the second sowing term was 106.0 mg less than in the first term (t_f – 11.26 > $t_{0.05}$ – 2.01). In the third sowing term, the biomass of the aboveground part of plants was even lower than that obtained in the second sowing term by 42.4 mg (t_f – 4.95 > $t_{0.05}$ – 2.01). Under the conditions of the fourth sowing term, the biomass of the aboveground part of barley plants was 462.3 mg, which is 44.3 mg less than in the third sowing term, the difference is significant at t_f – 5.31 > $t_{0.05}$ – 2.01. At the fifth sowing term, the lowest value of the biomass parameter was 421.7 mg, which was 40.6 mg less than the same indicator of the fourth sowing term (t_f – 4.59 > $t_{0.05}$ – 2.01). The analysis of the data on the weight of the dry matter of the aboveground part of the barley plant also shows a pattern of its significant decrease when the sowing dates are shifted by every 10 days from the first date of 10 March. The respective values were found to be 130.7 ± 3.7 mg; 97.0 ± 2.3 mg; 83.3 ± 1.9 mg; 71.7 ± 2.6 mg; 63.0 ± 1.8 mg. The difference between the data of the first and second sowing periods of 33.7 mg is significant (t_f – 7.75 > $t_{0.05}$ – 2.01). In the third sowing term, the dry matter weight was significantly lower than in the second term – by 13.7 mg (t_f – 4.60 > $t_{0.05}$ – 2.01), and in the fourth sowing term it was even lower than in the third term – by 11.6 mg (t_f – 3.60 > $t_{0.05}$ – 2.01). The lowest value for this analysis was found at the latest sowing date of 63.0 mg, where the difference was 8.7 mg and was also significant compared to the data obtained at the fourth sowing date (t_f – 2.75 > $t_{0.05}$ – 2.01).

It was proved that the area of leaf surface of barley plants according to the state of development at the beginning of the tillering process at different sowing dates was also at different levels of significance. In the second sowing term, the index was significantly lower than in the first term by 2.3 cm^2 (t_f – 3.90 > $t_{0.05}$ – 2.01). When spring barley was sown on 30 March, the leaf area was even significantly smaller by 1.4 cm^2 compared to the data obtained in the second term, with t_f – 2.64 > $t_{0.05}$ – 2.01. At the fourth sowing date, 10 days after the third, the leaf area decreased by another 1.3 cm^2 (t_f – 2.5 > $t_{0.05}$ – 2.01). Accordingly, under the condition of barley plants development at the fifth sowing date at the beginning of the tillering process, the leaf surface area was the smallest – 11.0 cm^2. Compared to the data of the fourth sowing term, the difference of 1.9 cm^2 is significant (t_f – 4.22 > $t_{0.05}$ – 2.01).

The obtained findings of the growth and development of barley plants at the time of the tillering phenomenon at different sowing dates in 2019 are presented in Table 2. The established index of barley plant biomass at the first term sowing is 699.5 mg, which is 125.8 mg higher than the same index obtained at the second term sowing, the difference is significant at the level of error significance of 5.0% (t_f – 14.70 > $t_{0.05}$ – 2.01). In the third sowing term, plant biomass was 56.8 mg less than in the second sowing term, a significant difference (t_f – 7.11 > $t_{0.05}$ – 2.01). Under the condition of sowing the fourth term, the biomass of barley plants was 464.2 mg and, accordingly, was significantly less than the biomass of plants of the third term by 52.7 mg (t_f – 6.25 > $t_{0.05}$ – 2.01). And in the case of the fifth sowing period, the figure was the lowest at 415.4 mg. When compared to the data obtained during the fourth term, a significant difference was 48.8 mg, where t_f – 5.61 > $t_{0.05}$ – 2.01.

***Table 2**. Characteristics of the growth and development of barley plants at the beginning of the tillering phenophase at different sowing dates (2019)*

Sowing period	Plant biomass, mg	Root system, mg		Aerial part, mg		Leaf area, cm^2
		raw biomass	dry matter	raw biomass	dry matter	
1	699.5 ± 6.3	64.7 ± 2.7	16.6 ± 0.60	634.8 ± 6.8	127.7 ± 2.5	17.5 ± 0.62
2	573.7 ± 5.8	42.7 ± 1.9	11.6 ± 0.50	531.0 ± 5.7	94.5 ± 2.0	14.9 ± 0.39
3	516.9 ± 5.5	29.4 ± 2.3	9.3 ± 0.44	487.5 ± 6.3	81.5 ± 2.1	13.8 ± 0.38
4	464.2 ± 6.4	19.2 ± 1.7	7.0 ± 0.56	445.0 ± 6.7	69.6 ± 2.4	12.4 ± 0.45
5	415.4 ± 5.9	11.5 ± 2.0	5.0 ± 0.48	403.9 ± 5.0	61.4 ± 2.3	10.1 ± 0.45

***Source:** developed by the authors*

Next, the indicators of barley growth and development were analysed according to the component part of the plant root system. In the first sowing term, the crude biomass of the root system of plants (64.7 mg) was significantly higher than in the second sowing term. The difference within 22.0 mg is significant at the error level of 5.0% (t_f – 6.67 > $t_{0.05}$ – 2.01). The biomass of the root system of barley plants of the third sowing period of 29.4 mg was also significantly lower than the corresponding indicators of the second sowing period (t_f – 4.46 > $t_{0.05}$ – 2.01). In an analogous pattern, the biomass of the root system of plants of the fourth sowing term is significantly lower compared to the biomass of the root system of the third term, the difference is 10.2 mg (t_f – 3.57 > $t_{0.05}$ – 2.01). The lowest biomass of the root system was found for plants in the fifth sowing term, where the index of 11.5 mg was lower compared to the data obtained in the fourth sowing term, the difference of 7.7 mg is significant (t_f – 2.94 > $t_{0.05}$ – 2.01). Assessment of barley plants development by indicators of root system dry matter at different sowing dates follows the pattern established according to the data of crude biomass. The highest value was obtained at the first sowing date – 16.6 mg and the lowest at the fifth date – 5.0 mg, the difference was 11.6 mg. For each subsequent sowing period, starting with the first, the figures have been consistently lower. The difference analysis for pairwise comparison of adjacent options is characterised by the following values. Indicators of the first and second sowing periods differed within 5.0 mg (t_f – 6.41 > $t_{0.05}$ – 2.01). Indicators of the second and third sowing terms by dry matter weight differed significantly by 2.3 mg (t_f – 3.48 > $t_{0.05}$ – 2.01). Likewise, the parameters of the data of the third and fourth sowing periods also differed by 2.3 mg at the established criterion t_f – 3.24 > $t_{0.05}$ – 2.01. The value of the indicator for the fifth sowing term compared to the data of the fourth term was significantly lower by 2.0 mg at the established criterion t_f – 2.74 > $t_{0.05}$ – 2.01.

The following analysis of the empirical data addresses the issue of plant growth and development according to the crude biomass of the aboveground part of barley plants at the beginning of the tillering process at different sowing dates. Comparison of the data from the first and second sowing dates showed a significant difference of 103.8 mg (t_f – 11.70 > $t_{0.05}$ – 2.01). When comparing the data of the second and third sowing periods, the difference was 43.5 mg with the best results of the second sowing period (t_f – 5.12 > $t_{0.05}$ – 2.01). The following analysis describes the comparison of the data from the third and fourth sowing dates, the difference at a significant level was 42.5 mg (t_f – 4.62 > $t_{0.05}$ – 2.01). And the difference between the data obtained in the fifth sowing term and the data of the fourth term of 41.1 mg was also significant (t_f – 4.92 > $t_{0.05}$ – 2.01). The analysis of the data on the dry matter content of the aboveground part of barley plants at different sowing dates corresponds to the pattern established in the data on crude biomass. The maximum values of dry matter in the plants of the first sowing term were established, where the index 127.7 mg was higher than the parameter established in the second sowing term by 33.2 mg, the difference was significant (t_f – 10.38 > $t_{0.05}$ – 2.01). At the third sowing date, dry matter in the amount of 81.5 mg was significantly lower than at the second sowing date by 13.0 mg (t_f – 4.48 > $t_{0.05}$ – 2.01). At the fourth sowing date, the dry matter content of the aboveground part of plants was significantly lower by 11.9 mg compared to the data obtained at the third sowing date, the difference was proved to be significant (t_f – 3.74 > $t_{0.05}$ – 2.01). And at the fifth sowing date, the dry matter content in the plants was the lowest at 61.4 mg. Compared to the data of the fourth sowing term, the indicator was significantly lower by 8.2 mg (t_f – 2.47 > $t_{0.05}$ – 2.01).

A detailed analysis of the data on the leaf area of spring barley plants shows that with each subsequent sowing date, 10 days after the first one on 10 March, the parameter significantly decreased. For instance, at the second sowing date, the leaf area of 14.9 cm was significantly lower than that of the first sowing date by 2.6 cm^2 at the level of significance of the error of 5.0% (t_f – 3.56 > $t_{0.05}$ – 2.01). When comparing the data of the second and third sowing terms by this indicator, the difference of 1.1 cm^2 was significant (t_f – 2.04 > $t_{0.05}$ – 2.01). At the fourth sowing date, at the time of the onset of the phenophase of three developed leaves, their surface area was 12.4 cm^2 and was significantly less than the data obtained at the third sowing date by 1.4 cm^2, t_f – 2.41 > $t_{0.05}$ – 2.01. And in the fifth sowing period, the value was the smallest – 10.1 cm^2. Compared to the data of the fourth sowing term, the difference of 2.3 cm^2 was significant (t_f – 3.65 > $t_{0.05}$ – 2.01).

The findings of studies of the growth and development of spring barley plants at different sowing dates at the onset of the tillering phenophase in 2020 are presented in Table 3. The index of plant biomass at the first sowing date was 749.0 mg, at the second sowing date it was significantly lower at 616.3 mg. The difference of 132.7 mg is significant, the t_f criterion is 14.71 > $t_{0.05}$ – 2.01. The biomass of barley plants at the third sowing term was significantly lower by 53.8 mg compared to the data obtained at the second sowing term, with t_f – 7.16 > $t_{0.05}$ – 2.01. The biomass of plants in the fourth sowing date was significantly lower than in the third sowing date. The difference was 60.3 mg (t_f – 7.56 > $t_{0.05}$ – 2.01). The lowest values of biomass of barley plants were obtained at the fifth sowing date of 455.3 mg. Accordingly, the difference of 46.9 mg compared to the data of the fourth term is significant (t_f – 5.35 > $t_{0.05}$ – 2.01).

***Table 3**. Characteristics of the state of growth and development of barley plants at the beginning of the tillering phenophase at different sowing dates (2020)*

Sowing period	Plant biomass, mg	Root system, mg		Aerial part, mg		Leaf area, cm^2
		raw biomass	dry matter	raw biomass	dry matter	
1	749.0 ± 7.0	70.5 ± 2.9	19.5 ± 0.70	678.5 ± 6.6	134.1 ± 3.1	18.9 ± 0.58
2	616.3 ± 5.7	46.5 ± 2.3	15.0 ± 0.61	569.8 ± 7.3	99.8 ± 2.7	16.1 ± 0.27
3	562.5 ± 4.9	33.9 ± 2.7	11.2 ± 0.59	528.6 ± 5.4	85.6 ± 2.9	15.0 ± 0.31
4	502.2 ± 6.3	20.5 ± 2.2	8.0 ± 0.40	481.7 ± 5.9	73.9 ± 2.0	13.5 ± 0.37
5	455.3 ± 6.1	13.3 ± 2.0	5.9 ± 0.47	442.0 ± 6.5	64.9 ± 2.4	11.4 ± 0.40

Source: *developed by the authors*

The crude biomass of the root system of plants at the first sowing date was characterised by the highest value of 70.5 mg. The difference in comparison with the same indicator at the second sowing date of 24.0 mg was significant (t_f – 6.49 > $t_{0.05}$ – 2.01). The index of crude biomass of the root system of barley plants of the third sowing period of 33.9 mg was 12.6 mg less than the data of the second sowing period, the difference was significant (t_f – 3.56 > $t_{0.05}$ – 2.01). When comparing the data from the third and fourth sowing dates, the difference was also significant at 13.4 mg (t_f – 3.85 > $t_{0.05}$ – 2.01). The lowest value of the crude biomass of the root system of barley plants was obtained at the fifth sowing date of 13.3 mg. The difference compared to the data of the fourth sowing period of 7.2 mg was significant (t_f – 2.42 > $t_{0.05}$ – 2.01). The analysis of the root system dry matter data depending on the sowing date showed a pattern where with each subsequent sowing date, 10 days after the first sowing on 10 March, there was a significant decrease in dry matter weight. The maximum value obtained in the first sowing period of 19.5 mg was 4.5 mg higher than in the second sowing period, where t_f – 4.89 > $t_{0.05}$ – 2.01. The value for the second sowing date of 15 mg was significantly higher than that of the third sowing date. The difference was 3.8 mg, Student's criterion t_f – 4.52 > $t_{0.05}$ – 2.01. The figure for the third sowing season is significantly higher than that for the fourth sowing season. The difference was 3.2 mg (t_f – 4.51 > $t_{0.05}$ – 2.01). And in the fifth sowing term, the value of 5.9 mg was significantly lower compared to the data of the fourth term. The difference of 2.1 mg was significant, Student's t_f – 3.44 > $t_{0.05}$ – 2.01.

The crude biomass of the aboveground part of plants decreased significantly from the first sowing date to each subsequent one. The value of 569.8 mg obtained in the second sowing period was significantly lower than in the first sowing period by 108.7 mg (t_f – 11.05 > $t_{0.05}$ – 2.01). The index of crude biomass of the aboveground part of plants in the third sowing term was 41.2 mg lower than that obtained in the second sowing term. The difference was significant (t_f – 4.54 > $t_{0.05}$ – 2.01). According to this pattern, the indicator of the fourth sowing term was significantly lower than the indicator of the third sowing term by 46.9 mg, t_f – 5.86 > $t_{0.05}$ – 2.01. The lowest value of the crude biomass of the aboveground part of barley plants was found when sowing in the fifth term, the difference to the data of the fourth sowing term of 39.7 mg was significant, Student's criterion t_f – 4.53 > $t_{0.05}$ – 2.01. The results of the analysis of the data on the dry matter content of the aboveground part of plants depending on the sowing dates show that with each subsequent term, starting from the first, the dry matter content of plants gradually decreased. Thus, in the second sowing term, the index of 99.8 mg was significantly lower than the same index obtained in the first sowing term by 34.3 mg (t_f – 8.35 > $t_{0.05}$ – 2.01). Accordingly, the third sowing season was significantly lower than the second sowing season. The difference was 14.2 mg at t_f – 3.59 > $t_{0.05}$ – 2.01. Comparison of the data of the fourth sowing period with the data of the third one was characterised by a significant difference of 11.7 mg (t_f – 3.32 > $t_{0.05}$ – 2.01). The comparison of the data of the fifth sowing term with the data of the fourth is determined by a significant difference at 9.0 mg, the Student's criterion t_f – 2.88 > $t_{0.05}$ – 2.01.

When characterising the leaf area data, a pattern of better results was also found at early sowing dates. The maximum value was obtained at the first sowing date of 18.9 cm^2. In the second sowing term, the data value was 2.8 cm^2 less, and a significant difference was found (t_f – 4.44 > $t_{0.05}$ – 2.01). The third sowing season was characterised by a lower value compared to the data obtained for the second sowing season. The difference of 1.1 cm^2 was significant, the Student's criterion t_f – 2.68 > $t_{0.05}$ – 2.01. At the fourth sowing date, the leaf surface area of the plants was 13.5 cm^2, which was 1.5 cm^2 less than the value of the third date, the difference was significant (t_f – 3.12 > $t_{0.05}$ – 2.01). The lowest value of the leaf area of barley plants was found for the fifth sowing date – 11.4 cm^2. The difference compared to the data of the fourth sowing term of 2.1 cm^2 was significant (t_f – 3.89 > $t_{0.05}$ – 2.01).

Thus, the dependence of growth and development of spring barley plants on sowing dates was established. According to the first, second, third, fourth, and fifth sowing dates, at the time of the tillering phenophase, the parameters of growth and development of spring barley plants significantly decreased. On average for three years, the respective values of the indicators were as follows: plant biomass – 723.6 mg; 594.5 mg; 539.2 mg; 482.8 mg; 434.9 mg; crude biomass of the root system – 67.5 mg; 44.6 mg; 31.6 mg; 19.8 mg; 12.3 mg; dry matter of the root system – 18.0 mg; 13.3 mg; 10.3 mg; 7.5 mg; 5.4 mg; crude biomass of the aerial part of plants – 656.1 mg; 549.9 mg; 507.6 mg; 463.0 mg; 422.5 mg; dry matter of the aerial part of plants – 130.8 mg; 97.1 mg; 83.5 mg; 71.7 mg; 63.1 mg; leaf surface area – 18.1 cm^2; 15.5 cm^2; 14.3 cm^2; 12.9 cm^2; 10.8 cm^2 (Table 4).

***Table 4**. Characteristics of the state of growth and development of barley plants at the beginning of the tillering phenophase at different sowing dates (average for 2018-2020)*

Sowing period	Plant biomass, mg	Root system, mg		Aerial part, mg		Leaf area, cm^2
		raw biomass	dry matter	raw biomass	dry matter	
1	723.6	67.5	18.0	656.1	130.8	18.1
2	594.5	44.6	13.3	549.9	97.1	15.5
3	539.2	31.6	10.3	507.6	83.5	14.3
4	482.8	19.8	7.5	463.0	71.7	12.9
5	434.9	12.3	5.4	422.5	63.1	10.8

***Source:** developed by the authors*

Accordingly, the results of the accumulation of spring barley plants of crude biomass, dry matter, leaf surface formation as a result of the use of vegetation factors before the onset of the tillering phenomenon at different sowing dates are of particular interest, which is to understand the rational use of environmental resources from the very beginning of growth and development.

The general theoretical issues of plant growth and development include changes that occur in the body of all biological species without exception. All biological species are characterised by developmental stages, vegetation phases, and stages of organogenesis (Kalenska *et al.*, 2018; Celestina *et al.*, 2023). The changes that occur in plants during growth and development can be distinguished both visually and by various research methods. Functionally, growth and development are the result of the interaction between the genotype of a biological object and the external environment. The external environment as an influence factor should be considered in terms of several important components, the key of which is the energy factor. Accordingly, the outcome of the interaction depends on both the structure of the DNA and the integral or total effect of the constituent environmental conditions, which results in the formation of the phenotype (Shaaf *et al.*, 2018). This allows establishing and evaluating the results of the interaction of the components based on the parameters of biometric indicators, dry matter content, plant model, and other parameters. If the same biological object is evaluated in an experiment under different environmental conditions, according to their impact on growth and development, the result of changes is directed by environmental or vegetation factors. Such results will provide a basis for understanding the need for rational and efficient use of vegetation factors to achieve maximum results in the formation of highly productive agrophytocenoses. Growth is usually characterised by quantitative changes that increase plant size, volume, and mass of newly formed cells. Plants grow continuously until the end of the vegetation cycle. Growth processes are followed by qualitative changes as a result of increasing plant size in a natural sequence. This is plant development. Growth creates a resource for the differentiation of new specialised tissues that form new organs, which ensures structural and functional changes in the entire organism.

A considerable role is played by plant growth characteristics in different phases of their development to fulfil the productivity potential of grain crops. S. Harkness *et al*. (2020) note that upon early sowing, plants use as much precipitation as possible during the winter period, which reduces plant losses from drought in the summer. Sowing at a late date usually does not produce large yields. While early sowing and emergence of seedlings always lead to faster flowering and maturation, thereby helping to avoid the negative effects of heat and drought, which usually results in higher grain yields. High temperatures tend to accelerate plant growth and development (Kiriziy & Stasik, 2022). The vegetation period becomes shorter, which leads to less radiation absorption and less biomass formation, and as a result, it leads to lower grain yields (Yadav *et al.*, 2022). P. Pal *et al*. (2018) noted that to ensure maximum barley yields, sowing should be carried out at the appropriate time, which must be observed so that the crop plants germinate well and use soil moisture efficiently.

The lower leaves play an important role in the formation of the root system and the ear in the early stages of plant development in cereals. The number and size of leaves, the value of net photosynthetic productivity directly affect the accumulation of dry matter (Dubytsky *et al.*, 2023; Stasyk *et al.*, 2021). Leaves are the main part of plant phytomass (Hospodarenko *et al.*, 2020). The size and dynamics of leaf surface development depends on many factors. In recent years, the sowing date has become an essential factor in the formation of the leaf assimilation surface area, which determines the intensity of plant growth and development. Environmental conditions affect the balance of phytohormones, the direction of physiological processes, changes in linear dimensions, plant habitus, etc., in plant growth and development, specifically in spring barley.

In the technology of spring barley cultivation, the results of the implementation of growth and development processes during the period from sowing to the onset of the tillering phenomenon, or the second and third stages of organogenesis, are of particular interest. The second and third stages of organogenesis are the period of plant development during which the yield structure of the first and second elements is laid down. To produce stable, high-quality crops during the growing season, one needs favourable weather conditions, which unfortunately cannot be controlled. It is known that by changing the timing of sowing, one can influence the supply of heat and solar radiation to plants. That is why sowing at the optimum time will help plants pass through the stages of organogenesis on which the future productivity of the agrophytocenosis depends.

CONCLUSIONS

This study established the regularity of reduction of spring barley biological potential, which provides the starting resource of plants in terms of development at the beginning of the tillering phenophase, depending on the sowing time with a delay of 10 days starting from March 10. The results of the analysis of the total biomass of plants for the first sowing period were on average 723.6 mg, for the second – 594.5 mg, for the third – 539.2 mg, for the fourth – 482.8 mg, and for the fifth – only 434.9 mg, which indicates significant changes under the influence of vegetation factors. Analysis of the development of the root system, which contributes to the formation of the aerial part of spring barley plants and characterises the obtained results of the maximum parameters of crude biomass 67.5 mg and dry matter 18.0 mg at the first sowing term. With each subsequent sowing date after 10 days, the values of these indicators were significantly lower, and respectively amounted to: crude biomass – 44.6 mg, 31.6 mg, 19.8 mg, 12.3 mg, and dry matter – 13.3 mg, 10.3 mg, 7.5 mg, 5.4 mg. According to the obtained pattern, the aerial part of plants is best provided with development conditions similarly to sowing on 10 March, when the indicators of plant biomass and dry matter were the best and were characterised by data of 656.1 mg and 130.8 mg, respectively. With each subsequent shift of the sowing date by 10 days, the obtained indicators became significantly lower, and accordingly amounted to: crude biomass – 549.9 mg, 507.6 mg, 463.0 mg, 422.5 mg, and dry matter – 97.1 mg, 83.5 mg, 71.7 mg, 63.1 mg.

The results of the analysis of the leaf surface area of plants, on which the photosynthesis process depends, indicate the expediency of early sowing. The maximum value of 18.1 cm^2 was obtained at the end of plant growth and development at the beginning of the tillering phenomenon at the first sowing date of March 10. Sowing every 10 days resulted in a significant reduction in leaf area, where the indicators were 15.5 cm^2, 14.3 cm^2, 12.9 cm^2, and 10.8 cm^2, respectively. The described regularities of fulfilment of spring barley plants development potential at the beginning of tillering phenophase depending on sowing dates represent the results of efficient use of environmental resources, specifically, vegetation factors. Prospects for further investigation lie in assessing the intensity of the tillering process of spring barley plants depending on the sowing time. Dependence of plant model formation on the degree of synchronisation and homogeneity of tillering shoots development compared to the main shoot. It is also promising to investigate the fulfilment of the potential of spring barley ear productivity in terms of the number of grains according to the sowing time.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Оцінка стану росту та розвитку рослин ячменю на початку фенофази кущення за різних строків сівби

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Анотація. Глобальні зміни кліматичних умов, які також відбулися і в Західному Лісостепу України сприяють раннім строкам сівби розпочинаючи вже з самого початку весняної пори року. У зв'язку з цим для забезпечення наукового обгрунтування технології вирощування ячменю ярого питання вивчення процесів росту та розвитку рослин до настання фенофази кущення, тобто другого та третього етапів органогенезу набуває особливої актуальності. Мета досліджень полягала у встановлені закономірності залежності процесів росту та розвитку рослин ячменю ярого від впливу факторів вегетації за різних строків сівби в умовах Західного Лісостепу України. Для узагальнення результатів досліджень застосовані наступні методи: загальнонаукові, в основі яких є об'єктивність, доказовість, відтворення та математично-статистичні – для обробки експериментальних даних. Встановлено залежність процесів росту та розвитку рослин ячменю ярого на основі показників біомаси рослин, сирої біомаси та вмісту сухої речовини кореневої системи і надземної частини рослин, а також площі листкової поверхні за проведеним аналізом на початку фази кущення від впливу строків сівби. Оцінено значущість дослідженого фактору за впливом умов забезпечення для максимальної реалізації потенціалу продуктивності ячменю ярого. В результаті виявлено закономірність за якою встановлено істотне зниження потенціалу продуктивності рослин ячменю з відтермінуванням на кожних наступних 10 днів починаючи від першого строку сівби проведеного 10 березня. Максимальні значення даних отримано за першого строку сівби, де біомаса рослини становила 723,6 мг; сира біомаса кореневої системи – 67,5 мг; суха речовина кореневої системи – 18,0 мг; сира біомаса надземної частини рослини – 656,1 мг; суха речовина надземної частини рослини – 130,8 мг і площа листкової поверхні – 18,1 см^2. В результаті наукового обгрунтування практична цінність роботи полягає в сприятливості ранніх строків сівби для забезпечення максимальної реалізації потенціалу продуктивності рослин за рахунок факторів вегетації

Ключові слова: біомаса рослин; сира біомаса; суха речовина; коренева система; надземна частина рослин; площа листкової поверхні; критерій Стьюдента

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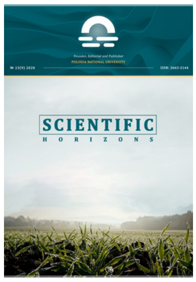

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Species composition of the main pests of aubergine in open soil conditions of the Right Bank Forest-Steppe of Ukraine

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Abstract. In the context of climate change and excessive anthropogenic pressure, the adverse effects of pests in agrocenoses are increasing, leading to considerable losses of crop production and economic damages. During the growing season, it is necessary to conduct phytosanitary monitoring to identify and control the number, spread, and intensity of pests, followed by determining the level of danger and

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developing relevant plant protection measures. For this, from 2008 to 2022, the species composition of pests in aubergine plantations in open ground conditions in the central part of the Right-Bank Forest-Steppe of Ukraine was studied. The study was conducted using conventional entomological methods. In aubergine plantations, 73 species of phytophagous insects from 25 families of 8 orders were found, which accounted for 93% of the pest structure, 2 species of mites (3%), 2 species of nematodes (3%), and one species of slugs (1%). The species diversity of insect phytophages was represented by insects from the orders: *Coleoptera* (20 species from 6 families), *Lepidoptera* (19 species from 5 families), *Homoptera* (14 species from 3 families), *Diptera* (9 species from 4 families), *Orthoptera* (5 species from 4 families), *Thysanoptera* (3 species from 1 family), *Hemiptera* (2 species from 1 family), *Hymenoptera* (1 species from 1 family). Among the ticks, the greatest damage was caused by the red spider mite (*Tetranychus urticae* Koch.), which on average was inhabiting 10-50% of the area. The average number of *Tetranychus urticae* Koch. was 8.5 specimens/plant, with up to 35-44% damage, which exceeded the EWP by 3.5-4.4 times. The colonisation of aubergine areas by naked slugs was not significant (up to 12%), but plant damage reached 10-14%. Among the insect phytophages, the largest area of plantations was infested with the Colorado potato beetle, larvae of the maybeetle, and gnawing scoops, which averaged 35-100%. The most harmful during the growing season were the Colorado potato beetle and the European mole cricket

Keywords: *Solanum melongena* L.; pests; phytophagous insects; phytosanitary condition; harmfulness; pest population density

INTRODUCTION

In the context of climate change and excessive anthropogenic pressure, the negative impact of pests in agrocenoses is increasing, leading to significant losses in crop production and economic damages. This forces agricultural producers to use even more chemical plant protection products, which leads to new environmental problems, including disruption of biological balance, changes in dominant pest species, their number and harmfulness, contamination of products with pesticide residues, etc. Furthermore, there are prohibitions and restrictions on the use of chemical pesticides in vegetable cultivation. Therefore, it is important to conduct phytosanitary monitoring to identify and control the number, spread, and intensity of pests, with the subsequent determination of their level of danger and development of relevant plant protection measures.

Harmful organisms are the primary causes of worldwide crop yield losses, and pest control plays a crucial role in ensuring food security, the efficient operation of agriculture, and it also impacts biodiversity (Alansary *et al.,* 2021; Skendžić *et al.,* 2021; Shah *et al.,* 2023). On average, globally, 10-28% of crop production is lost to pests (IPPC Secretariat, 2021). Phytophagous insects have an important economic value among harmful organisms in agrocenoses of vegetable crops. The main significant obstacles to increasing the volume of vegetable production in open ground conditions, including aubergine fruits, are global climate changes and extreme weather events, along with harmful organisms that create additional challenges for agricultural producers (Anuar *et al.,* 2023).

S. Kumar *et al.* (2019), I. Mostoviak and O. Demyanyuk (2020) noted that the harmful effects of phytophages and phytopathogens have increased. This increase is associated with the neglect of agrotechnologies for growing agricultural crops, violations of crop rotation, excessive use of chemical plant protection agents, or non-compliance with the technologies of their introduction, leading to the formation of resistance in harmful organisms to pesticides. Additionally, climate changes contribute to these challenges. The key factors that influence the diversity and abundance of pest arthropods in an agroecosystem are the landscape context and farming practices. All these factors collectively contribute to the deterioration of the phytosanitary condition of agrocenoses, an increase in biological and ecological risks in agroecosystems, and a decrease in plant productivity (Flores-Gutierrez *et al.,* 2020; Jaworski *et al.,* 2023).

FAO (n.d.) also estimates annual global vegetable losses due to insect damage alone at 15-20% during cultivation and 18-20% during storage. The harmful effect of phytophagous insects on agricultural crops is manifested in the damage to above-ground and underground organs of plants, the transmission of diseases, which leads to a violation of the physiological status and a decrease in yield, losses during storage of the grown crop, which ultimately affects economic indicators. The natural and climatic conditions of Ukraine are favourable for cultivating most vegetable crops in open ground, allowing for the expansion of their range and the introduction of innovative technologies to provide the population with useful and high-quality vegetables. According to O. Zakharchuk (2021), if innovations in the production and development of the food industry are used, Ukraine can considerably improve its position in world markets. In addition, vegetable growing is a highly profitable and competitive branch of the domestic agricultural sector of economy, which, in recent years, has also become one of the leaders in increasing the export of domestic products. However, Ukraine still has an extremely insufficient range and variety of high-vitamin products. Furthermore, as a result of the hostilities, there is a shortage of vegetable and melon products, which affects the country's food and environmental security, and the food problem needs to be addressed with due regard to the possibilities of domestic production.

Aubergine (*Solanum melongena* L.) is one of the essential vegetable crops in domestic and global vegetable production and nutrition of the population. It also serves as as the main raw material for the canning industry. Aubergine fruit is a nutritious product with minimal calories, but maximum biological value. In Ukraine, aubergines are cultivated in open ground on an area of about 5.1 thsd ha, primarily at small farms and personal homesteads of the population (State Statistics Service of Ukraine, n.d.). Ukraine ranks fourth in aubergine production among European countries and 25th globally (AtlasBig, n.d.).

However, the level of yields of open-air vegetable crops in Ukraine is insufficient compared to European countries, due to a series of technological problems and the critical phytosanitary condition of agrocenoses (Shchetina *et al.*, 2023). At the same time, the irrational use of pesticides has a powerful impact on the environment, specifically on natural enemies of pests, destroys ecological balance, and causes outbreaks of secondary pests. All these issues are exacerbated by climate change, when new ecological niches are created that allow insect pests to establish and spread in new geographical regions and move from one region to another. That is why the purpose of this study was to investigate the species composition of pests in aubergine (*Solanum melongena* L.) plantations under open field conditions in the central part of the Right-Bank Forest-Steppe of Ukraine.

MATERIALS AND METHODS

The study was conducted at Uman National University of Horticulture. During 2008-2022, the phytosanitary state of aubergine plantations was monitored on the territory of Cherkasy Oblast as representative of the Right Bank Forest-Steppe. Each year route inspections of more than 70 ha of aubergine plantations were conducted on the household plots and farms in Cherkasy Oblast. Recording of pests was performed during route inspections in the growing season of the crop in the main phases of their development using the BBCH scale (international scale of plant growth and development phases (phenological phases)): shoots (BBCH 0-10), first true leaf (BBCH 11-12), 5 leaves (BBCH 13-15), stem growth (BBCH 21-29), budding (BBCH 50-59), flowering (BBCH 60-69), fruit formation and growth (BBCH 70-79), fruit ripening (BBCH 81-89), technical ripeness (BBCH 97-99).

For this, the methods generally accepted in entomology were used. Insects were caught at 07:00 am to 10:00 am using nets. These included visual inspection of plants, sweep-net method, soil excavation, Petliuk's box, and Barber's traps. Petliuk's box, resembling a truncated pyramid without a bottom and a top, with a layer of cotton wool attached to the inner surface of its walls, was employed to catch and record small jumping insects. The surface area was 0.1 m² (with the size of the side wall at the bottom being 316 mm, at the top 800 mm, and with a height of 350 mm).

For the study of terrestrial entomofauna, Barber's traps were used – polyethylene glasses, filled to one-third with a fixative (ethylene glycol) and buried so that their upper part was at the level of the soil and tightly adjoined to it. The diameter of the upper part of the glass was 7 cm, and its height was 9.5 cm. Pests were removed from the traps once every 10 days, placed on cotton mattresses and labelled. The species of insects were identified using binoculars and markers. The taxonomic affiliation of the entomological material was analysed in the laboratory using modern insect keys, atlases, and available online electronic versions of keys to different groups of invertebrates (Royal Entomological Society, n.d.). The study was conducted following the standards of the Convention on the Protection of Biological Diversity (1992). Damage screening was also performed in between the active sampling. The infestations were monitored thoroughly from roots, branches, small branches, leaves, fruits, flowers, and shoots of the plants. The damage was surveyed, documented, and photographed for future reference.

RESULTS AND DISCUSSION

According to the results of monitoring studies on the phytosanitary state of aubergine agrocenoses, it was established that plants are damaged by 73 types of insects, two types of mites, two types of nematodes, and one type of slugs. The structure of the harmful complex in the aubergine agrocenosis is presented in Figure 1.

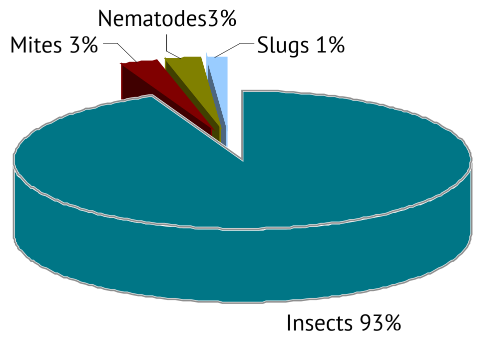

***Figure 1**. The structure of the harmful complex of aubergine agrocenosis, Cherkasy Oblast (average for 2008-2022), %*
***Source:** developed by the authors of this study*

Two members of the Heteroderidae family were discovered among the nematodes (order Tylenchida): golden potato nematode (*Meloidogyne marioni* Woll.) and root-knot nematode (*Globodera rostochiensis* Woll.).

Naked slugs (*Kailie gliemeži*) are among slug species. Phytophagous mites from the order Acariformes (acariform mites) were represented by red spider mite (*Tetranychus urticae* Koch.) from the family Tetranychidae and tomato russet mite (*Aculops lycopersici* Massee) from the family Eriophyidae.

Red spider mite caused the most significant damage, occupying an area ranging from 10% to 50% during the years 2008-2022. The average number of spider mites was 8.5 individuals per 1 plant, and plant damage was recorded at the level of 35-44%. During the research period, the maximum number of mites was 18 individuals/plant, and plant damage was recorded at the level of 50%. Exceeding of economic threshold was 3.5-4.4 times. The most massive infestation of aubergine plantings by the red spider mite was in 2015 and made up 50%, and in 2019 it was 30%. A high number of phytophagous individuals was recorded at the level of 5, 6, and 8 individuals/plant in 2018, 2009, and 2012, respectively. The exceeding of the economic threshold ranged from 2.5 to 5.0 times, with the economic threshold set at 3-5 individuals per leaf and affecting 10% of inhabited plants.

Over the years of research, naked slugs (*Kailie gliemeži*) were also discovered in the aubergine agrocenosis. The percentage of inhabited areas was not significant on average and amounted to 1-12% (max 15%), while the average number of pests was 1-4 specimens/m^2. However, plant damage was 10-14%. It was noted that the number and distribution of slugs depended not only on weather conditions, but also on certain agricultural measures. Thus, the use of plant residues, which are often used for fertilisation in private farms, contributed to the development and reproduction of slugs. Favorable weather conditions, specifically warm winters, and moderately warm, wet weather in the spring-summer period caused an outbreak of mass reproduction of these pests, up to 7 specimens/m^2 were detected in aubergine plantations, and plant damage reached 22%. Among aubergine pests, class Insecta has the greatest variety of species, which accounted for 93% of the pest structure (Fig. 1). The harmful entomofauna includes representatives of:

Order Coleoptera:

- Chrysomelidae – *Leptinotarsa decemlineata* Say., *Phyllotreta cruciferae* Goeze, *Phyllotreta undulata* Kutsch., *Psylliodes affinis* Payk., *Phyllotreta vittata* Redt., *Phyllotreta nemorum* L., *Phyllotreta atra* F., *Phyllotreta crucifera* Goeze., *Phyllotreta armoraciae* Koch., *Entomoscelis adonidis* Pallas;
- Coccinellidae – *Coccinella septempunctata* L.;
- Curculionidae – *Baris coerulescens* Scop., *Baris carbonaria* Boh., *Baris chlorizans* Germ., *Ceutorrhynchus quadridens* Panz., *Ceuthorrhynchus assimilis* Payk.;
- Elateridae – *Agriotes lineatus* (L.), *Agriotes sputator* L.;
- Nitidulidae – *Meligethes aeneus* F.;
- Scarabaeidae – *Melolontha melolontha* L.

Order Diptera:

- Agromyzidae – *Linomyza bryoniae* Kalt., *Delia platura* Mg.;
- Anthomyidae – *Delia brassicae* Bouche, *Delia floralis* Fallen;
- Sciaridae – *Bradysia brunnipes* Mg., *Pnyxia scabiei* Hop.;
- Tipulidae – *Tipula oleracea* L., *Tipula paludosa* Mg., *Tipula vernalis* Mg.

Order Hemiptera:

- Pentatomidae – *Eurydema ventralis* Kol., *Eurydema oleracea.*

Order Homoptera:

- Aleyrodidae – *Trialeurodes vaporariorum* Westw., *Aleurodes proletella*;
- Aphididae – *Myzodes persicae* Sulz., *Aphis gossypii* Glov., *Macrosiphum euphorbiae* Thom., *Rhopalosiphum padi* L., *Schizaphis graminum* Rondani, *Macrosiphum (Sitobion) avenae* F., *Brachycolus (Cuernavaca) noxius* Mordv., *Brevicoryne brassicae* L.;
- Cicadinea – *Hyalesthes obsoletus* Sign., *Laodelphax striatella* L., *Psammotettix striatus* L., *Macrosteles laevis* L.

Order Hymenoptera:

- Tenthredinidae – *Athalia rosae* L.

Order Lepidoptera:

- Gelechiidae – *Phthorimaea operculella* Zell., *Plutella maculipennis* Curt., *Tuta abcoluta* Meyr.;
- Noctuidae – *Scotia segetum* Denis&Schiff., *Lacanobia oleracea* L., *Mamestra brassicae* L., *Helicoverpa armigera* Hub., *Hydraecia micacea* Esp., *Laphygma exigua* Hb., *Euxoa agricola* B., *Euxoa tritici* L., *Autographa gamma* L.;
- Pieridae – *Aporia crataegi* L., *Pieris brassicae* L., *Pieris rapae* L., *Pontia edusa* Fabr.;
- Pyralidae – *Evergestis forficallis* L., *Evergestis extimalis* Scop.;
- Sphingidae – *Manduca quinquemaculata* Haworth.

Order Orthoptera:

- Acrididae – *Locusta migratoria* L.;
- Gryllidae – *Gryllus campestris* L.;
- Gryllotalpidae – *Gryllotalpa gryllotalpa* L.;
- Tettigoniidae – *Tettigonia viridissima* L., *Decticus verrucivorus* L.

Order Thysanoptera:

- Thripidae – *Thrips tabaci* Lindeman, *Heliothrips haemorrhoidalis*, *Haplothrips tritici* Kurd.

Thus, phytophagous insects, which comprise members of 73 species from 25 families and 8 orders, are present in the structure of the harmful entomocomplex of aubergine. The taxonomic structure of the harmful entomocomplex is dominated by representatives of the orders Coleoptera (20 species), Lepidoptera (19 species), and Homoptera (14 species) (Fig. 2). In total, the representatives of these orders made up 73% of the structure of the harmful entomocomplex.

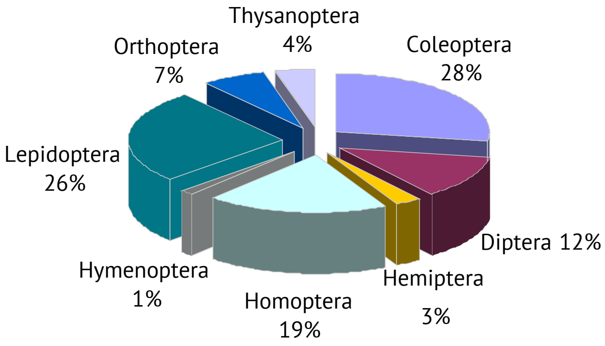

***Figure 2**. Taxonomic structure of the harmful entomocomplex of aubergine agrocenosis, Cherkasy Oblast, 2008-2022, %*
***Source:** developed by the authors of this study*

The order Coleoptera was found to have a large diversity of species, with 20 species belonging to 6 families: leaf beetles (Chrysomelidae), click beetles (Elateridae), dung beetles (Scarabaeidae), ladybird beetles (Coccinellidae), snout beetles (Curculionidae), and nitidulid beetles (Nitidulidae). Their share in the structure of the entomocomplex was 28%. The families of leaf beetles and snout beetles were represented by the largest number of species – 10 and 5, respectively. Notably, the seven-spot ladybird (*Coccinella septempunctata* L.) from the family Coccinellidae (coccinellids), being entomophagous, can form large clusters and damage the fruits under certain weather conditions, which were recorded during the monitoring.

The order of lepidopterans (Lepidoptera) is represented by 5 families: noctuid moths (Noctuidae), gelechiid moths (Gelechiidae), pyralid snout moths (Pyralidae), Sulphur butterflies (Pieridae), and hawk moths (Sphingidae). Their share in the structure of the harmful entomocomplex was 26%. The Noctuidae family exhibited the highest species diversity (9 species), with two dominant and highly destructive species: *Scotia segetum* Denis&Schiff. (turnip moth) and *Lacanobia oleracea* L. (bright-line brown eye). The order of homopterans (Homoptera) included 14 species from 3 families: true aphids (Aphididae), leafhoppers (Cicadellidae), and whiteflies (Aleyrodidae). Their share in the structure of the complex of harmful phytophagous insects is 19%. The Aphididae family has the largest number of species (8).

Representatives of two-winged (Diptera) and orthopterous insects (Orthoptera) were represented by species from 4 families and made up 12% and 7%, respectively, in the structure of the entomocomplex. The order Diptera, which included about the same number of species as the crane fly family (Tipulidae), had a greater diversity of species in the agrocenosis of aubergine: 3 species and 2 species each – families of dark-winged fungus gnats (Sciaridae), flower flies (Anthomyidae) and leaf miner flies (Agromyzidae). Similarly, the order of Orthoptera was also represented by the same number of species (1-2) from the families of mole crickets (Gryllotalpidae), bush crickets (Tettigoniidae), crickets (Gryllidae), and true grasshoppers (Acrididae).

The order Thysanoptera, represented in the entomocomplex, comprised only two species from the thrips family (Thripidae), constituting 4% of the overall entomocomplex structure. The lowest species diversity, consisting of only one family with one to two species each, was observed in the representatives of the Hymenoptera and Hemiptera orders. Together, these orders accounted for 4% of the harmful entomocomplex structure within the aubergine agrocenosis. Specifically, the families represented were true sawflies (Tenthredinidae) and stink bugs (Pentatomidae).

During the growing season in the aubergine agrocenosis, eight dominant phytophagous insect species were identified, causing significant damage as the most common pests: *Leptinotarsa decemlineata* Say., *Trialeurodes vaporariorum* Wstw., *Agriotes sputator* L., *Myzodes persicae* Sulz., *Scotia segetum* Denis&Schiff., *Lacanobia oleracea* L., *Thrips tabaci* Lindeman and *Gryllotalpa gryllotalpa* L. The results of the monitoring showed that the largest area of aubergine plantations was inhabited by Colorado potato beetle and the larvae of click beetles and cut worms (on average from 35 to 100%) (Table 1). The common cabbage leafhopper and cotton thrips were found to occupy the smallest area of plantings, on average between 5% and 30%.

Leptinotarsa decemlineata Say. and its larvae caused the highest level of damage to aubergine plants, occurring both at the early stages of development and throughout the entire vegetation period – 33-90% (max 100%), which exceeded the economic threshold by 1.3-4.0 times. At the same time, the pest population averaged within 15-45 specimens/m^2 over the years of research, with some years recording up to 70 specimens per 1 m^2. The green peach aphid also exhibits a relatively high abundance (24-36 specimens/plant) and causes substantial plant damage, ranging within 38-52%, with a maximum recorded damage of 86%. This species serves as a dangerous carrier of numerous viruses, forming large colonies on plant leaves. By sucking out the juice from the plants, it leads to leaf deformation, delays in plant growth, and underdeveloped fruits.

It was observed that the population of the greenhouse whitefly was 1.2-2.2 times higher than that of the economic threshold, with an average of 12-22 specimens per plant. In years with the maximum number of pests (40 specimens per plant), the greenhouse whitefly population was four times higher. Consequently, plant damage was recorded at levels ranging within 15-22%, with a maximum of 30%.

Table 1. *Dominant species of phytophagous insects in aubergine agrocenoses, average for 2008-2022*

Pest	Populated area, %	Average number of pest per 1 plant or m^2	Damaged plant, %
Leptinotarsa decemlineata Say.	75-100 (100)*	15-45 (70)	33-90 (100)
Myzodes persicae Sulz.	46-100 (100)	24-36 (42)	38-52 (86)
wireworms – larvae of dark click beetle (*Agriotes* spp)	35-57 (94)	1-6 (10)	8-16 (20)
Cut worms: *Scotia segetum* Denis&Schiff.; *Lacanobia oleracea* L.	40-75 (85)	1-6 (8)	8-15 (30)
Trialeurodes vaporariorum Wstw.	10-25 (70)	12-22 (40)	15-22 (30)
Gryllotalpa gryllotalpa L.	5-30 (45)	1-3 (5)	9-17 (25)
Thrips tabaci Lindeman	10-20 (40)	2-8 (12)	7-10 (15)

Note: **in brackets – the maximum (max) value of the indicator*
Source: *developed by the authors of this study*

Among beetles from the family click beetles (Elateridae), the dark beetle (*Agriotes sputator* L.) caused significant damage, with populations damaging up to 20% of plants. On average, the economic threshold exceedance was recorded at 1.2 times, doubling in years with the highest pest numbers. Notably, one of the primary factors influencing outbreaks of this phytophagous population is the weather conditions of the year. A high density of cutworm populations was also observed, causing damage to 8-15% of the plants, with a maximum recorded damage of 30%.

In certain years, the population levels of turnip moth and bright line brown-eye significantly surpassed the economic threshold (by 6-8 times), reaching up to 6-8 specimens/m^2. The thrips complex in the aubergine agrocenosis was dominated by cotton thrips (*Thrips tabaci* Lindeman) with an average number of 2-8 specimens/m^2 (max 12). This species caused damage to 7-10% of plants (max 15%). Importantly, the level of the economic threshold was not exceeded over the years of research. The mole cricket population ranged within 1-3 specimens/m^2 (max 5), resulting in plant damage reaching up to 25%. Notably, the exceedance of the the economic threshold was observed at 2-5 times. This polyphagous insect has a two-year development cycle and causes significant damage to many agricultural crops. Long-term monitoring studies have shown that each stage of vegetation of aubergine plants is characterised by a certain composition of pests (Fig. 3).

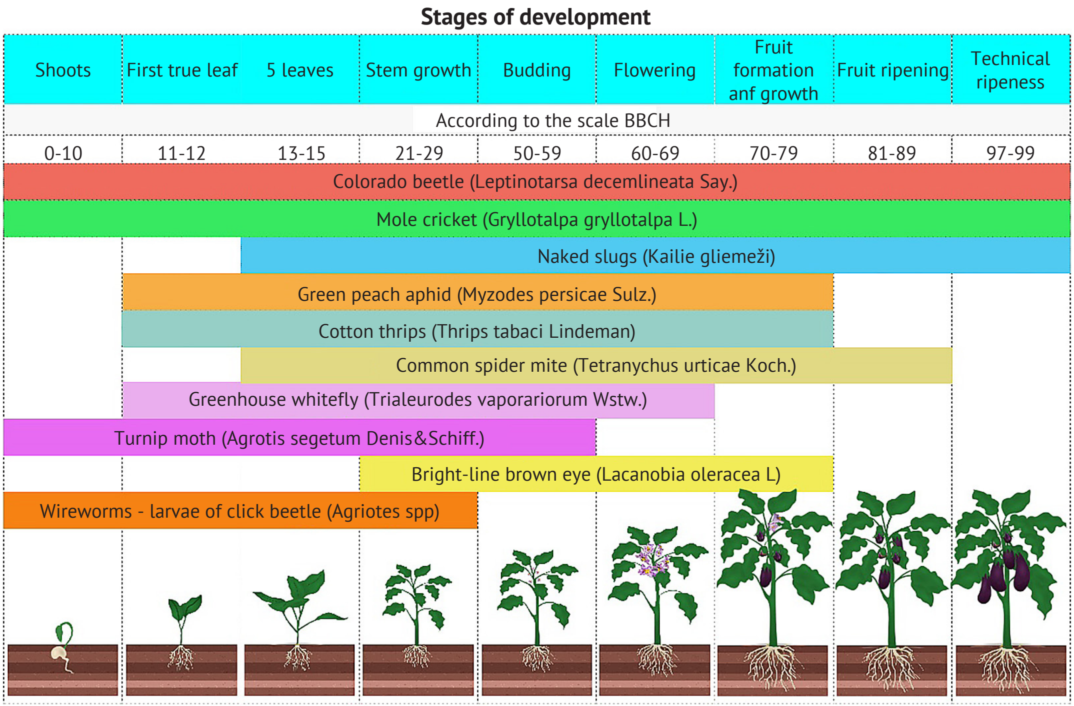

Figure 3. *The periods of harmful activity of the main phytophages (insects, mites, slugs) according to the development phases of aubergine plants*
Source: *developed by the authors of this study*

It was found that *Leptinotarsa decemlineata* Say. and *Gryllotalpa gryllotalpa* L. were dominant and most harmful species throughout the entire growing season from germination to the technical ripeness of the fruits. *Leptinotarsa decemlineata* Say. is a phytophagous insect that causes considerable damage to plants of the nightshade family (Solanaceae) in all phases of development both in the Right Bank Forest Steppe and throughout Ukraine. It was proved that as the population of the *Leptinotarsa decemlineata* Say. increases, the assimilation surface of plant leaves is more extensively damaged, leading to greater potential yield losses, which can reach up to 80% (Kroschel *et al.,* 2020; Islam *et al.,* 2020). It was established that warm winters contributed to the overwintering of the pest in the soil, with an average mortality rate of 7-10%. During the research, colonisation of aubergine plants was observed as early as the stage of planting seedlings in open ground in the beginning of the second decade of May. At the end of the third decade of May, the beginning of egg laying by the pest was recorded. Phytophage became widespread during the phases of stem growth (BBCH 21-29), budding (BBCH 50-59), and flowering (BBCH 60-69).

Gryllotalpa gryllotalpa L. is an extremely dangerous polyphagous pest. The greatest harmfulness of this insect is observed at the end of May-mid-July. During this period, the phytophagous insects damage young aubergine plants by gnawing the stem and roots, causing the plants to quickly wither, turn yellow, and dry up. The next active period of mole cricket harmfulness was observed from mid-August to the end of September, during which the pests prepare for wintering and feed mostly on fruits and stems of plants.

Additionally, during the initial stages of aubergine plant development, the larvae of the dark click beetle (*Agriotes sputator* L.) and the turnip moth (*Scotia segetum* Denis & Schiff.) were active, causing significant damage. Their activity persisted until the budding phase (BBCH 50-59) and flowering (BBCH 60-69), respectively. Throughout the years of research, the number of larvae of the dark click beetle and caterpillars of the turnip moth in the soil during spring (first decade of April) remained mostly constant, ranging within 0.6-0.9 specimens/m^2. The second generation of turnip moth in summer was observed in the second decade of August. During the initial stages, specifically the first true leaf phase (BBCH 11-12), cotton thrips (*Thrips tabaci* Lindeman), green peach aphid (*Myzus persicae* Sulz.), and greenhouse whitefly (*Trialeurodes vaporariorum* Wstw.) were detected on the plants.

The greenhouse whitefly (*Trialeurodes vaporariorum* Wstw.) is a polyphagous insect that feeds on 128 plant species from 48 families and causes significant economic damage to vegetable and ornamental crops in greenhouses (Wenda-Piesik & Piesik, 2021). Nevertheless, throughout many years of research, authors observed the presence of this pest from the emergence of the first true leaf to the flowering phase (BBCH 11-12 to BBCH 60-69). This pest reduces both the quality and quantity of plant productivity by feeding on plant sap, producing honeydew, and transmitting plant-pathogenic viruses. During the period of active plant growth and before the phase of fruit formation, the bright line brown eye (*Lacanobia oleracea* L.) caused significant damage. Caterpillars of the first generation damaged 6-8% of plants, while the second generation caused damage to up to 18%.

Aubergine (Solanum melongena) is the third most important vegetable in Asia and is of particular importance in the Mediterranean belt. Although global production of aubergine fruit has been increasing in recent years, productivity is limited due to insect and pathogen damage and abiotic stresses (Alam & Salimullah, 2021). Each region has its own dominant pest species due to specific conditions, and their impact on plants and harmful effects depend on a series of environmental and technological factors (Subedi *et al.*, 2023; Asni *et al.*, 2024).

In Bangladesh, 488 insects were collected from an aubergine field. The collected insects belonged to 20 species of 21 families and 10 orders. The percentage of insects in different taxonomic orders ranged within 0.4-33.6. Among the taxonomic orders, Hemiptera (33.6) was the most dominant, followed by Coleoptera (28.3%), Hymenoptera (12.7%), Diptera (8.8%), Lepidoptera (7.6%), Odonata (2.6%), and Dermaptera (2.5%). Other orders, namely Orthoptera (2%), Dictyoptera (1.2%) and Thysanoptera (0.4%), showed an extremely low percentage of abundance (Amin et al., 2018). Thus, in Indonesia, 10 species of insects from 8 families were found on green aubergine plants: *Epilachna* sp., *Paracoccus marginatus*, *Empoasca* sp., *Atractomorpha crenulata*, *Cassida circumdata*, *Stenocatantops angustifrons*, *Oxya japonica*, *Phlaeoba fumosa*, *Bemisia tabaci*, and *Bactrocera dorsalis*. Among them, *Bemisia tabaci* has the highest dominance index of 1.41 (Rahayu, 2022).

F. Sánchez-Bayo (2021), M. Mohammed *et al.* (2023) identified seven insect orders associated with Solanum lasiocarpum. Diptera had the largest number of species (31.4%), Coleoptera – 26.9%, Hymenoptera – 23.1%. Current studies also show a significant diversity of insect phytophages in aubergine plantations and a wide range of insect species from the orders Coleoptera, Lepidoptera, Homoptera Diptera and Orthoptera. The greatest damage was caused by the red spider mite (*Tetranychus urticae* Koch.). *Leucinodes orbonalis* is a key pest of aubergine in the Indian subcontinent and occurs throughout most of southern Asia with records mostly from India and Bangladesh (EFSA Panel on Plant Health, 2024). The the aubergine fruit and shoot borer (EFSB), *Leucinodes orbonalis* larvae (especially third- and fourth- instars) bore into tender shoots, resulting in the plant ultimately wilting and becoming unable to bear fruits. In addition, the larvae bore into fruits, making them unmarketable. The occurrence of the pest inside the plant body saves them from insecticidal contact. Escaping from insecticides and a lack of natural resistance in cross-compatible species make EFSB the major aubergine pest. Furthermore, aubergine fruit borers (*Helicoverpa armigera*), stem borers (*Euzophera perticella*), hadda beetles (*Epilachna vigintiopunctata*), as well as some sucking aphids and parasitic nematodes (*Meloidogyne* spp), are important pests affecting aubergine cultivation.

F. Taiwo *et al.* (2020), A. Ekholm *et al.* (2022) focus on insect pests of aubergine at three growth stages (vegetative, flowering, and fruiting), with peak activity observed in the fourth week after planting in open ground. It was observed that *Z. variegatus* and *Epilachna* spp. destroyed the leaves, while *S. litoralis* and *L. ornabolis* severely damaged flowers and fruits, with about 70% of the fruits destroyed by the harvesting stage. The colonisation of aubergine plants by *S. litoralis* and *L. ornabolis* began five weeks after planting. Therefore, when developing measures to control insect pests of aubergine, it is necessary to consider the biological characteristics of both the target plant and the pest, which was done in the present study.

CONCLUSIONS

Thus, a considerable biodiversity of harmful entomofauna was found in the aubergine agrocenosis, which is of great economic significance at all stages of plant development during the growing season. On the territory of the Cherkasy Oblast (central part of the Right Bank Forest Steppe of Ukraine) 73 species of phytophagous insects, two species of phytophagous mites, two species of nematodes and one species of slugs were found on aubergine plants. Insects from 25 families from 8 orders constitute the structure of the harmful entomocomplex of aubergine. The taxonomic composition is predominantly represented by members of the orders Coleoptera (20 species), Lepidoptera (19 species), and Homoptera (14 species), collectively occupying 73% of the harmful entomocomplex structure.

Representatives of the orders Diptera and Orthoptera were represented by species from 4 families and occupied 12% and 7%, respectively, in the structure of the entomocomplex. The order Thysanoptera (thrips) was represented by only two species from the thrips family (Thripidae), accounting for 4% of the entomocomplex structure. Among representatives of the Hymenoptera and Hemiptera orders, the least species diversity (1 family, 1-2 species) was observed, collectively occupying 4% of the harmful entomocomplex structure. The dominant species that caused significant damage to aubergine plants throughout the growing season were: *Leptinotarsa decemlineata* Say., *Trialeurodes vaporariorum* Wstw., *Agriotes sputator* L., *Myzodes persicae* Sulz., *Scotia segetum* Denis&Schiff., *Lacanobia oleracea* L., *Thrips tabaci* Lindeman, *Gryllotalpa gryllotalpa* L. Exceeding of the economic threshold was 1.2-8 times. It stays important to constantly monitor the number and spread of certain dominant species of pests in aubergine plantations in open ground conditions and, if necessary, apply environmentally friendly plant protection methods.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Видовий склад основних шкідників баклажана в умовах відкритого ґрунту Правобережного Лісостепу України

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Анотація. В умовах змін клімату та надмірного антропогенного навантаження посилюється негативна дія шкідників в агроценозах, що призводить до значних втрат продукції рослинництва і економічних збитків. Протягом вегетаційного періоду необхідно проводити фітосанітарний моніторинг для виявлення та контролю чисельності, поширення та інтенсивності розвитку шкідливих організмів з подальшим визначенням рівня небезпеки та розробкою відповідних заходів захисту рослин. З цією метою з 2008 по 2022 рік досліджували видовий склад шкідників у насадженнях баклажана в умовах відкритого ґрунту в центральній частині Правобережного Лісостепу України. Дослідження проводили з використанням загальноприйнятих ентомологічних методів. У насадженнях баклажана виявлено 73 види комах-фітофагів із 25 родин із 8 рядів, що в структурі шкідників становило 93 %, 2 види кліщів (3 %), 2 види нематод (3 %) і один вид слимаків (1 %). Видове різноманіття комах-фітофагів було представлено комахами з рядів: *Coleoptera* (20 видів із 6 родин), *Lepidoptera* (19 видів із 5 родин), Homoptera (14 видів із 3 родин), Diptera (9 видів із 4 родин), *Orthoptera* (5 видів із 4 родин), Thysanoptera (3 види з 1 родини), Hemiptera (2 види з 1 родини), *Hymenoptera* (1 вид з 1 родини). Серед кліщів найбільшої шкоди завдавав кліщ павутинний звичайний (*Tetranychus urticae* Koch.), яким у середньому було заселено 10-50 % площ. Середня чисельність *Tetranychus urticae* Koch. становила 8,5 особин/рослину, за їх пошкодження до – 35-44 %, що перевищувало економічний поріг шкодочинності у 3,5-4,4 раза. Заселення площ баклажана голими слимаками було не значним (до -12 %), проте пошкодження рослин сягало 10-14 %. Серед комах-фітофагів найбільшу площу насаджень було заселено жуком колорадським, личинками коваликів, совками підгризаючими, що в середньому становило 35-100 %. Найбільш шкідливими впродовж вегетації були колорадський жук і капустянка звичайна

Ключові слова: *Solanum melongena* L.; шкідники; комахи-фітофаги; фітосанітарний стан; шкідливість; щільність популяції шкідників

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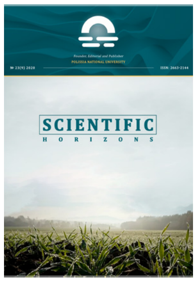

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Identification and monitoring of agricultural land contaminated by military operations

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Abstract. Russia's attack on Ukraine has caused widespread contamination of agricultural land, which is now an urgent environmental problem that is important for human health and sustainable development. In this regard, the purpose of this study was to analyse the impact of military operations in Ukraine on agricultural land. To fulfil this purpose, a study was conducted at the Educational and Research Centre of Mykolaiv National Agrarian University, which included data collection and analysis in different regions of Ukraine, including Dnipro, Mykolaiv, and Zaporizhzhia oblasts. It was found that in Dnipropetrovsk Oblast, soil contamination with lead exceeds the maximum permissible concentration (MPC) by 3 times and fluoride by 1.5 times; in Mykolaiv Oblast, the concentration of lead exceeds the MPC by 5 times, the content of zinc, copper, fluoride, and oil products by a quarter; and in Zaporizhzhia Oblast, the

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concentration of lead exceeds the MPC by 11.17 times, the content of zinc and fluoride is increased by half, petroleum products – by 35%, and phosphates – by 30%. Furthermore, the study confirmed the impact of military operations on the physical and chemical properties of soils, specifically, an increase in the acidity of the soil environment (pH) and the density of the topsoil. To reduce the impact of war on soil and the ecosystem, it is necessary to monitor and assess the effects of military operations, develop and implement environmentally friendly technologies, and restore and rehabilitate the affected areas. The findings of this study can be used to prepare recommendations for the authorities to minimise the environmental impact of military operations on soils

Keywords: agricultural sector; martial law; soil density; heavy metals; petroleum products

INTRODUCTION

Agricultural land is of great significance to society, ensuring food security, economic development, social stability, and environmental sustainability. They create jobs, support rural communities, and help maintain environmental balance. Agriculture is also an essential part of cultural heritage, shaping traditions and customs (Racioppi *et al.*, 2022). Russia's war against Ukraine has caused enormous damage to the country's infrastructure and economy and has put food supplies in Ukraine and beyond at risk. The agricultural sector, which is one of the leading sectors of the economy, has been affected by the hostilities, which may have long-term adverse consequences for the country's further development.

The destruction of agricultural land, infrastructure, and equipment, as well as restrictions on access to these resources, have led to a substantial decline in agricultural production. According to V. Câmpeanu (2022), this decline in production could have grave consequences: food shortages, rising food prices, and a general deterioration in food security. Furthermore, a shortage of agricultural products could affect the country's export capabilities, leading to a decrease in foreign exchange earnings and further economic decline. As a result, this situation could lead to a humanitarian crisis, as access to basic foodstuffs will be limited for many citizens. M.E. Bildirici *et al.* (2022) and V. Biyashev *et al.* (2023) note that the hostilities on the territory of Ukraine, initiated by Russian aggression, have led to serious pollution of agricultural land, which poses a threat to public health, ecology, and the economy. Restoring these lands is critical to ensuring food security.

The study of the impact of hostilities on agricultural land contamination has attracted the attention of many scientists from various fields, including ecology, agronomy, geography, and chemistry. Specifically, A. Drobitko *et al.* (2023) believe that hostilities cause considerable soil contamination with heavy metals and explosives, which have a long-term impact on the environment. Therefore, it is important to systematically monitor pollution and implement bioremediation technologies to clean the affected areas. Pollution of agricultural land has a significant negative impact on soil fertility and agricultural productivity. D. Fiott (2022) believes that pesticides and explosives can alter the chemical composition of soils, reducing their ability to support plant growth. Therefore, developing a strategy aimed at soil restoration, including the use of special agronomic measures and the introduction of resistant plant varieties, is crucial.

J. Bluszcz and M. Valente (2020) note that contamination by explosives and their decay products is a serious threat to agricultural land. These chemical compounds can adversely affect soil microorganisms, which play a key role in maintaining and improving soil fertility. To determine the degree of contamination, detailed laboratory tests are required to accurately assess the level of toxicity. Furthermore, effective methods of chemical detoxification and phytoremediation for the treatment of contaminated land need to be developed. T. Glauben *et al.* (2022) argue that chemical detoxification involves the use of special chemicals to neutralise toxins, while phytoremediation uses plants that can absorb and accumulate harmful substances, thereby cleansing the soil. This approach requires a comprehensive effort that incorporates research, innovative technologies, and coordination between multiple organisations and institutions.

Identifying and monitoring contaminated land is a major step in identifying the sources of pollution and developing effective remediation measures, as well as implementing environmental restoration and protection programmes. M. Griffiths (2021) emphasises the significance of applying a comprehensive approach to the identification and monitoring of contaminated land. T.S. Adebayo and A.O. Acheampong (2021) emphasise that only systematic and detailed research will minimise risks and develop effective strategies aimed at restoring ecological balance and ensuring sustainable agricultural development. This includes the use of the latest technologies to analyse soil conditions, development of methods for cleaning and restoring land, and close cooperation between scientific institutions, government agencies, and agricultural enterprises (Fedoniuk *et al.*, 2024).

Thus, various studies confirm that agricultural land contaminated due to military operations is a multifaceted problem that requires a comprehensive approach. However, despite the considerable amount of research, there are some gaps in the literature, especially regarding integrated methods that combine field surveys, laboratory analysis, and remote technologies to better understand the extent of contamination. The introduction of modern monitoring technologies and the development of effective remediation strategies are critical to ensuring environmental safety and sustainable development of the agricultural sector (Zibtsev *et al.*, 2024). The joint efforts of scientists from different fields can help solve this important problem and secure the future for the affected areas.

The purpose of this study was to assess the extent and nature of the impact of hostilities on agricultural land in Ukraine. To fulfil this purpose, the following tasks were performed: to establish the level of contamination of agricultural land with harmful substances, to determine the impact of military operations on the physical and chemical properties of soils, and to develop strategies for the restoration and management of contaminated and damaged agricultural land.

MATERIALS AND METHODS

The study was based on a set of official sources, specifically, the information base included the Internet resources of the Ministry of Environmental Protection and Natural Resources of Ukraine, the Ministry of Agrarian Policy and Food of Ukraine, and the State Statistics Service of Ukraine, as well as monographic and periodical scientific literature. The theoretical framework of this study included key provisions and findings of scientific research investigating the problems and consequences of the Russian-Ukrainian war, as well as the scientific theories and approaches related to the impact of military operations on ecosystems by anthropogenic pollution, risks and consequences of environmental disasters.

To assess the level of soil contamination caused by military operations, a comprehensive study was conducted at the Training and Research Centre of Mykolaiv National Agrarian University to assess the condition of Ukrainian agricultural land before and after the Russian aggression. To this end, scientific data was collected and analysed in different regions of Ukraine, including Dnipro, Mykolaiv, and Zaporizhzhia Oblasts. Specifically, the data before the invasion were collected in 2020-2021, and during – in 2024. Initially, mapping data and reports from local authorities were collected to help identify areas that could potentially be contaminated. To this end, the areas of the regions with suspected contamination were identified and sites for soil sampling were established.

Number and location of plots for each region:

1. Dnipropetrovsk Oblast:

Contaminated areas:

- Site 1 – Ivanivka village (Dnipro region), where the hostilities took place;
- Site 2 – the city of Pavlohrad, where the shelling took place;
- Site 3 – Marianka village (Synelnykove region), which was affected by the explosions.

Clean areas:

- Site 1 – Orlivshchyna village (Novomoskovsk region), where no hostilities took place;
- Site 2 – Tomakivka village (Tomakivka region), where the natural soil condition has been preserved.

2. Mykolaiv Oblast:

Contaminated areas:

- Site 1 – Mykolaiv city, central district, where the shelling was recorded;
- Site 2 – Shyroke village (Snihurivka region), which was affected by hostilities;
- Site 3 – Blahodatne village (Bashtanka region), which was bombed.

Clean areas:

- Site 1 – Kovalivka village (Mykolaiv region), where no hostilities took place;
- Site 2 – Parutyne village (Mykolaiv region), where the natural conditions are still stable.

3. Zaporizhzhia Oblast:

Contaminated areas:

- Site 1 – Zaporizhzhia city, Khortytskyi region, where the shelling took place;
- Site 2 – Orikhiv city, which has sustained serious damage;
- Site 3 – Mala Tokmachka village (Polohy region), where intense fighting took place.

Clean areas:

- Site 1 – Komyshuvakha village (Zaporizhzhia region), where no military operations were recorded;
- Site 2 – Novoiakovlivka village (Zaporizhzhia region), where the natural soil condition has been preserved.

Thus, for each region, three contaminated sites and two clean sites were selected for research. This allows comparing the condition of the soil before and after the hostilities and assess the level of soil contamination. The soil contamination study methodology included: sampling in the areas after the Russian invasion from the following depths: 0-10 cm, 10-20 cm, and 20-30 cm to obtain a representative and average sample; preparation of soil samples for analysis (drying and grinding to the required fraction); determination of the content of pollutants in soil samples (lead, fluorine, cadmium, mercury, sulphur, nickel, copper, cobalt, zinc, and oil products), soil pH and soil density; analysis of the data obtained. For each of the identified elements, a pollution index (P) was calculated based on the ratio of the element's concentration in the soil to its maximum permissible concentration (MPC), as well as a total pollution index for these elements – as the sum of the indices.

At the beginning of the study, a thorough check of the area for explosive devices was mandatory. A soil drill was used to collect soil samples, while the collected soil samples were examined in the laboratories of Mykolaiv National Agrarian University. Specifically, the content of heavy metals was determined by gas chromatography with a GC-MS mass spectrometry detector (Shimadzu, Japan); the concentration of nitrates, phosphates, and petroleum products – by gas chromatography; the reaction of the soil environment (pH) – using a PCE-PH 18 PCE pH meter (Instruments, Germany); the density of the topsoil – according to the method of M.A. Kachinsky.

All collected data was subjected to statistical analysis. To process the research results for statistical significance, the multivariate method of analysis of variance MANOVA was used, using Microsoft Excel software and the Statistica 10 software package. The differences between the results were assessed using the Student's t-test at a significance level $P \leqslant 0.05$.

RESULTS

The military actions launched by Russia have led to considerable environmental disasters in Ukraine, particularly in its nature reserves. As a result of these actions, large areas of forests were destroyed, and unique ecosystems were seriously damaged. Over 200,000 hectares of territory are contaminated with shells, mines, and ammunition fragments, which poses massive risks to natural biodiversity and public health. Explosions of rockets, artillery shells, bombs, drones, and multiple launch rocket systems cause the destruction of the top fertile soil layer. This layer, which has been formed over centuries, is key to agriculture and ecosystem conservation. The explosions also release toxic compounds into the soil, including carbon dioxide, nitrous oxide, water vapour, formaldehyde, cyanide vapour, and other toxicants. These substances not only reduce soil quality, but can also migrate into water systems, threatening human and animal health.

The war considerably deteriorates the physical and chemical properties of the soil, and as a result, its fertility decreases. Specifically, changes in soil structure can lead to a loss of water and nutrient retention capacity, which are critical for plants. Explosions can also cause mechanical damage to the soil, making it difficult to use for agriculture. Ukrainian soils have already lost about 30% of their humus over the past century due to intensive agriculture and other anthropogenic factors. Military actions only accelerate this process (Panfilova, 2021). Humus is a vital component of soil that ensures its fertility and stability. The loss of humus leads to a decrease in the productivity of agricultural land, which can have serious economic consequences.

Ukraine's nature reserves, which are home to a variety of flora and fauna, are also affected by the hostilities. Pollution, habitat destruction, and the direct destruction of plants and animals lead to a considerable decline in biodiversity (Shevchuk, 2024). Restoring these ecosystems could take decades and require significant efforts and resources. According to the Ministry of Environmental Protection and Natural Resources of Ukraine, the condition of Ukrainian land has deteriorated substantially since the full-scale invasion. Soil contamination increased by an average of 30-60% compared to the full-scale invasion (Fig. 1).

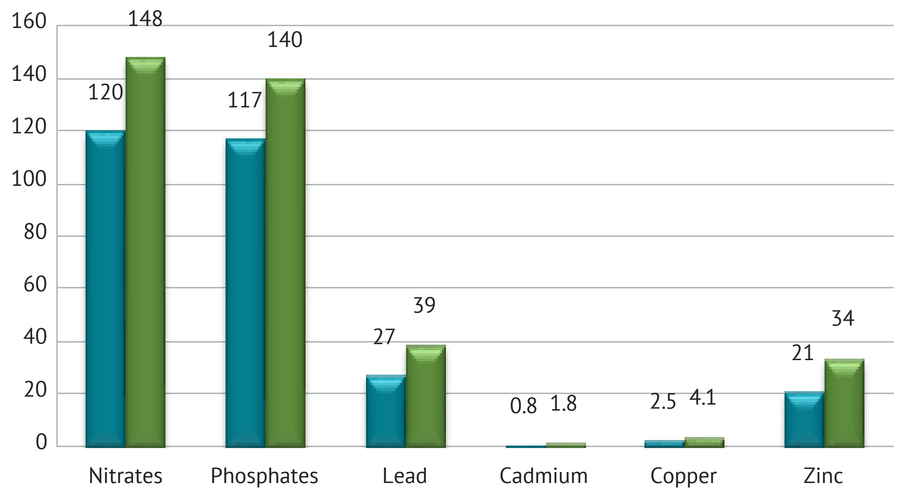

***Figure 1**. Changes in pollution of Ukrainian land before and after the full-scale invasion of Russia, mg/kg*
***Source:** compiled by the authors of this study*

Thus, the state of soil contamination in Ukraine before the war was relatively safe, as the content of harmful substances met safety standards and did not exceed the MPC. However, after prolonged hostilities, there has been a significant increase in the content of heavy metals, nitrates, phosphates, and petroleum products, which exceeds the standard levels. The findings of the study of Ukrainian agricultural land after the Russian aggression in Dnipro, Mykolaiv, and Zaporizhzhia oblasts confirmed that the level of soil contamination is high, especially in areas where active military operations were ongoing, and the concentration of pollutants in the soil exceeds the permissible limits (Table 1).

Table 1. *Level of soil contamination after the invasion of Russia, mg/kg of soil*

Harmful substance	Pollutant content			MPC
	Dnipropetrovsk Oblast	Mykolaiv Oblast	Zaporizhzhia Oblast	
Mercury	2	2.2	2.4	2.1
Copper	3.4	3.8	4.1	3
Zinc	22.5	30	35.4	23
Lead	18.4	29.5	67	6
Sulphur	178	182	192	160
Fluoride	3.4	3.5	4.2	2.8
Cadmium	1.6	1.7	2	1.5
Nickel	4	4.3	4.6	4
Cobalt	4.5	5.2	5.7	5
Petroleum products	968	1,240	1,350	1,000
Phosphates	105	125	157	120
Nitrates	127	126	154	130

Source: *compiled by the authors of this study*

Specifically, in the Dnipropetrovsk Oblast, soils are contaminated with various harmful substances, including lead and fluoride, which significantly exceed the MPC, with lead exceeding the MPC by three times and fluoride – by one and a half times. Copper, sulphur, and cadmium also exceed the permissible levels, although to a lesser extent. Other pollutants, such as mercury, zinc, nickel, cobalt, petroleum products, phosphates, and nitrates, are within or close to the permissible limits. Analysis of soil contamination in Mykolaiv Oblast also shows a fivefold exceedance of the MPC for lead – 29.5 mg/kg, zinc content – 30% above the MPC, copper and fluoride – 25% above the MPC, and petroleum products – 24% above the MPC. Other harmful substances, such as mercury, copper, sulphur, cadmium, nickel, cobalt, phosphates, and nitrates, also exceed permissible levels, requiring immediate measures to clean and control soil contamination. In Zaporizhzhia Oblast, the concentration of lead was found to be 11.17 times higher than the MPC, while zinc content was increased by 54%, fluorine – by 50%, petroleum products – by 35%, and phosphates – by 30%. The Zaporizhzhia Oblast has considerable soil contamination with harmful substances, which indicates serious environmental problems and harmful effects on people. Such soil contamination can also lead to disruption of ecosystems, changes in land fertility, and the quality of crops grown. Therefore, urgent measures are needed to clean the soil and prevent further contamination. In the three regions of Ukraine under study (Dnipropetrovsk, Mykolaiv, and Zaporizhzhia oblasts), there is a critical level of soil pollution, with total indices of 14.55, 18.43, and 25.56, respectively. The largest exceedances of the MPC were recorded for lead, petroleum products, copper, and zinc, especially in Zaporizhzhia Oblast (Table 2).

Table 2. *Indices of soil contamination with harmful substances*

Harmful substance	Soil pollution index		
	Dnipropetrovsk Oblast	Mykolaiv Oblast	Zaporizhzhia Oblast
Mercury	0.95	1.05	1.14
Copper	1.13	1.27	1.37
Zinc	0.98	1.3	1.54
Lead	3.07	4.92	11.17
Sulphur	1.11	1.14	1.2
Fluoride	1.21	1.25	1.5
Cadmium	1.07	1.13	1.33
Nickel	1	1.08	1.15
Cobalt	0.9	1.04	1.14
Petroleum products	0.97	1.24	1.35
Phosphates	0.88	1.04	1.31
Nitrates	0.98	0.97	1.18
Total pollution index	14.55	18.43	25.56

Source: *compiled by the authors of this study*

Notably, the war also affected the acidity (pH) of soils through several mechanisms. The use of explosives leads to the release of nitrates and sulphates, which acidify the soil. The destruction of residential buildings and warehouses promotes the spread of building materials such as concrete and cement, which release alkalis that also change the pH of the soil. Leaks of oil products from military equipment cause soil acidification, while the use of chemicals, including defoliants and agrochemicals, changes the composition of the soil and affects its acidity (pH). The degradation of vegetation as a result of military operations reduces the amount of organic matter in the soil and weakens its buffering properties, making the soil more vulnerable to changes in pH. Military operations also lead to groundwater contamination, which increases the content of acids or alkalis in the soil (Lopushnyak *et al.*, 2022). Together, these factors cause significant changes in soil pH, which can have dire consequences for local ecosystems and agricultural land, reducing soil fertility and making it difficult to grow crops that require a neutral or near-neutral pH to grow optimally. The study found that military actions on the part of Russia affected the change in the pH of the environment in the soils of the oblasts under study (Table 3).

***Table 3**. Indicators of soil reaction*

Oblast	Soil layer		
	0-10 cm	10-20 cm	20-30 cm
Dnipropetrovsk Oblast	5.8	5.9	6.3
Mykolaiv	6	6.2	6.5
Zaporizhzhia	5	5.5	6.3

***Source:** compiled by the authors of this study*

According to the data obtained, in Zaporizhzhia Oblast, the pH of the soil environment is the most acidic among the three oblasts, especially in the tilth (0-10 cm) soil layer. In the Mykolaiv region, the soil pH is more neutral, which may contribute to better conditions for plant growth. In the Dnipropetrovsk Oblast, pH values range from slightly acidic to almost neutral in the deeper soil layers. Changes in pH can affect the availability of nutrients to plants and the overall health of the ecosystem. The military and anthropogenic load causes a mechanical impact on the soil, which lies in deformation of the soil cover. The high weight of tracked and wheeled vehicles used by the military leads to soil compaction, which has negative consequences, such as disruption of the water balance of soils, erosion, soil over-compaction, and the transition of water-saturated dispersed soils to a fluid state due to the destruction of structural bonds under dynamic load (Shaforost *et al.*, 2024). Furthermore, the mechanical impact is accompanied by chemical contamination of the soil, which leads to the permanent decommissioning of the land and a ban on its use. These consequences could have a serious impact on agricultural development and the environment in the future. The findings suggest that soil density varies by region and depth. In Dnipropetrovsk Oblast, the density of the topsoil (0-30 cm) is 1.22 g/cm^3, in Mykolaiv Oblast – 1.25 g/cm^3, and in Zaporizhzhia Oblast – 1.19 g/cm^3 (Table 4).

***Table 4**. Soil density, g/cm^3*

Oblast	Soil layer			
	0-10 cm	10-20 cm	20-30 cm	0-30 cm
Dnipropetrovsk	1.15	1.21	1.3	1.22
Mykolaiv	1.19	1.24	1.32	1.25
Zaporizhzhia	1.12	1.2	1.26	1.19

***Source:** compiled by the authors of this study*

Thus, pollution and changes in the physical and chemical properties of Ukrainian land are a genuine issue, especially after the invasion of Russia. Many of these contaminants have become even more dangerous as they are caused by the use of military equipment and weapons. The study found that military operations have a significant impact on soil conditions, particularly in the east of Ukraine. The negative effects of this impact include soil contamination due to hostilities and illegal dumping of chemicals, which poses a serious threat to both the health of the local population and the environment.

The findings indicate the need for immediate measures to minimise the impact of the hostilities on the soil and ecosystem. This includes the development and implementation of environmentally friendly technologies for military operations, enhanced monitoring and assessment of the impact of military operations on soil and the ecosystem, and measures to restore and reclaim the affected areas. It is also important to educate military personnel on environmental safety and implement programmes to restore and protect soil and the ecosystem, including cooperation with international organisations and experts to share practices and receive support in minimising the negative impact of military operations on the environment.

To reduce the risk of soil contamination, it is also necessary to establish strict controls over the use of pesticides and chemicals in agriculture and industry. Regular monitoring of soil contamination, especially in areas affected by military operations, will help to identify hazards promptly and take the measures necessary to prevent further spread of contamination. For soil restoration, it is recommended to use special technologies and materials that will help restore soil fertility and biological composition, such as biological fertilisers and cultivation of special plant species. The Ukrainian authorities should take decisive steps to reduce the risk of soil contamination, including monitoring its quality and cleaning the soil if necessary. Furthermore, it is crucial to restore peaceful control over the territories occupied by Russian militants to ensure the safety of the local population and to carry out monitoring and soil clean-up activities.

DISCUSSION

The war started by Russia has led to a significant increase in soil pollution in Ukraine, which poses a threat not only to human health but also to global food security. According to various scientific studies, the military conflict has led to the contamination of a large area of land equivalent to the size of an average European country (De Groot *et al.*, 2022). Ukraine has already struggled with soil pollution due to decades of industrial activity and poor waste management practices. The ongoing war has only exacerbated the problem, leading to the destruction of infrastructure and waste management systems, and increasing the risk of soil, water, and air pollution (Babenko *et al.*, 2021).

The study confirmed that toxic elements such as lead, cadmium, arsenic, and mercury from ammunition and weapons leach into the soil, contaminating the food chain, and posing a risk to agricultural production. Furthermore, M. Cláudia *et al.* (2022) show that soil, water, and air pollution has long-term consequences for the ecosystem, and therefore it is urgent to address this problem. The findings also suggest an increase in toxic substances in the soil, which will lead to degradation of its physical and chemical properties and disruption of the biological balance, affecting various aspects of the agro-ecosystem, including soil fertility and crop quality. According to O. Belcher *et al.* (2019), microorganisms that ensure soil fertility become vulnerable to toxins, which will reduce humus formation and adversely affect soil structure.

The conducted study confirms the statement of M. Jankowski and M. Gujski (2022), who note that as the war intensifies, pollutants from munitions explosions can seriously damage the soil and the environment, which affects crop growth, quality, and quantity of crops. The researchers also note that soil contamination with toxicants disrupts the ecological balance and has a harmful effect on soil biota, which is essential for maintaining soil fertility. The results highlight the significance of controlling the level of toxic contamination of soil and water sources to ensure food safety. As a confirmation, V. Gamajunova *et al.* (2021) also emphasise that toxic substances can actively accumulate in plants, which affects food safety and has a potentia lly negative impact on human health. This poses a threat, as consumption of such products can cause negative consequences for the body, depending on the type of toxic substances.

A. Drobitko and A. Alakbarov (2023) showed that in the areas where military operations took place, the concentration of metals in the soil considerably exceeded the permissible standards and posed a significant threat to environmental stability. This contamination will have far-reaching consequences for the local population, who may suffer negative health impacts through contact with contaminated soil and water sources. Furthermore, environmental degradation can exacerbate socio-economic problems, making post-war recovery more difficult. Comprehensive environmental programmes aimed at cleaning the soil and restoring the ecosystem, as well as the introduction of strict legal regulations to prevent similar situations in the future, may help to address the existing threats. In support of this, K.K. Khaletska and N.O. Sydorenko (2019) find that the war in Ukraine will lead to a large drop in agricultural yields. The Russian invasion has resulted in over 20% of Ukraine's arable land being occupied, Russia systematically attacking agricultural infrastructure and farmers' facilities, and soil contaminated with toxic substances that could take decades or even hundreds of years to remediate.

Thus, the problem of soil contamination in Ukraine is truly complex and requires a comprehensive approach to solving. Limited resources, political instability, and the ongoing war pose considerable obstacles to the effective implementation of environmental protection measures. However, the findings and opinions of researchers such as A. Panfilova and V. Fedorchuk (2022) point to initiatives aimed at reducing soil pollution and improving environmental sustainability. One of these initiatives is the development of waste management systems aimed at efficient use and recycling of waste to reduce its impact on the environment. An additional initiative, according to H. Van Meijl *et al.* (2022), is to promote sustainable agricultural practices that involve the use of less fertiliser and plant protection products, as well as more frequent use of organic tillage methods. These approaches help to preserve soil fertility and prevent soil contamination with toxic substances.

V. Astrov *et al.* (2022) also believe that a monitoring system should be developed that could become a key tool for the prevention and detection of pollution in real time. It would ensure constant monitoring of the environment, allowing for a prompt response to any new sources of pollution and minimising their impact on natural resources and human health. This approach would improve the effectiveness of soil and water quality control, ensuring safety for all life processes. Furthermore, V. Lopushnyak *et al.* (2022) also concur that restoring ecosystems and soil fertility is a critical task for Ukraine. This will require a comprehensive approach, including clean-up of contaminated areas, reforestation, implementation of sustainable agricultural practices, and soil monitoring. International cooperation and support can play a significant role in this process by providing the necessary resources and technology for recovery. A. Panfilova (2021) notes that it is crucial to use reliable environmental monitoring methods to accurately assess the environmental impact of military operations. These include remote sensing, mathematical and simulation models, mobile laboratories, and unmanned aerial vehicles as particularly effective means. The use of these technologies makes it possible to collect objective data on the state of the environment during and after military conflicts, which is critical for making informed decisions on the conservation and restoration of ecosystems (Kravchuk *et al.*, 2023).

Thus, Russia's invasion of Ukraine was a turning point for the entire world with significant geopolitical consequences. The war is changing the global landscape, disrupting the world order, and threatening security and stability around the world. In a globalised world, the effects of war in one region are felt far beyond its borders through complex supply chains and economic ties. Soil contamination in Ukraine caused by the hostilities is affecting the agricultural sector and has a potentially negative impact on global food safety. Considering the urgency and seriousness of the soil pollution problem in Ukraine, it is vital to emphasise the need for joint efforts by the government, international organisations and civil society. Implementing effective measures to reduce the environmental impact of industrial and military activities is an urgent task. Sustainable management strategies, improved waste management, and innovative approaches to environmental monitoring will be key to achieving environmental safety and sustainability goals. Only through cooperation and global support can successful solutions be provided to minimise the negative impact on the environment and ensure a sustainable improvement in the quality of life of the population.

CONCLUSIONS

The military conflict started by Russia in Ukraine has created a serious threat of soil contamination, destruction of ecosystems, forests, and natural biodiversity. The findings of this study of the state of Ukrainian agricultural land after the Russian aggression reflect serious soil pollution problems in the Dnipropetrovsk, Mykolaiv, and Zaporizhzhia oblasts.

The study found that in the Dnipropetrovsk Oblast, soils are contaminated with various harmful substances, including lead and fluoride, which exceed the MPC by 3 and 1.5 times, respectively. In Mykolaiv Oblast, the concentration of lead exceeds the MPC by 5 times, zinc is 30% higher than the MPC, copper and fluoride exceed the limit by 25%, and petroleum products – by 24%. In Zaporizhzhia Oblast, the concentration of lead exceeds the MPC by 11.17 times, the content of zinc has increased by 54%, fluorine by 50%, petroleum products – by 35%, and phosphates – by 30%. The total indices of soil pollution in the three regions of Ukraine under study are 14.55, 18.43, and 25.56, respectively. Furthermore, military actions have affected the pH of the soil environment towards increased acidity, while the military and anthropogenic load has caused mechanical impact on the soil, which has led to soil compaction. The density of the topsoil (0-30 cm) varies by region and depth and is 1.22 g/cm^3 in Dnipropetrovsk Oblast, 1.25 g/cm^3 in Mykolaiv Oblast, and 1.19 g/cm^3 in Zaporizhzhia Oblast.

To reduce the impact of the hostilities on the soil and ecosystem, a range of measures must be taken at once. This includes the development and implementation of environmentally friendly technologies, systematic monitoring and assessment of the impact of military operations on soil and ecosystems, and restoration and reclamation of damaged areas. It is also important to strengthen legal control over the use of fertilisers, plant protection products, and other chemicals in agriculture and industry, and to regularly monitor soil pollution, especially in the areas most affected by Russia's invasion. Soil restoration also requires the use of special technologies and materials that will restore soil fertility and biological composition. The authorities should take various measures, including monitoring the quality of the soil and cleaning it if necessary, as well as restoring civilian control of the territories occupied by Russian troops.

Prospects for further investigation include exploring the possibilities of using reclaimed soils for ecosystem and biodiversity regeneration. Limitations of this study lie in the difficulty of accessing some areas affected by military conflicts in terms of data collection and due monitoring.

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None.

CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Ідентифікація та моніторинг забруднених сільськогосподарських земель внаслідок бойових дій

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Анотація. Напад росії на Україну спричинив широкомасштабне забруднення сільськогосподарських земель, що наразі є нагальною екологічною проблемою, важливою для здоров'я людей та сталого розвитку країни. У зв'язку з цим, мета дослідження полягала в аналізі наслідків військових дій в Україні на сільськогосподарські землі. Для досягнення мети було проведено дослідження на базі Навчально-науково-практичного центру Миколаївського національного аграрного університету, яке включало збір та аналіз даних у різних регіонах України, зокрема у Дніпропетровській, Миколаївській та Запорізькій областях. Встановлено, що у Дніпропетровській області забруднення ґрунтів свинцем перевищує гранично допустимі концентрації (ГДК) у 3 рази, а фтором – у 1,5, у Миколаївській області концентрація свинцю перевищує ГДК в 5 разів, вміст цинку, міді, фтору та нафтопродуктів – на чверть, а у Запорізькій області концентрація свинцю перевищує ГДК в 11,17 разів, вміст цинку, фтору збільшено на половину, нафтопродуктів – на 35 %, а фосфатів – на 30 %. Крім того, у дослідженні підтверджено, що існує вплив військових дій на фізико-хімічні властивості ґрунтів, зокрема, відмічено збільшення кислотності реакції ґрунтового середовища (pH) та щільності орного шару ґрунту. Для зменшення впливу війни на ґрунти та екосистему, слід здійснювати моніторинг та оцінку наслідків військових дій, розробляти та впроваджувати екологічно безпечні технології, а також проводити відновлення та рекультивацію постраждалих територій. Результати дослідження можуть бути використані для підготовки рекомендацій органами влади щодо мінімізації екологічного впливу військових дій на ґрунти

Ключові слова: аграрний сектор; військовий стан; щільність ґрунту; важкі метали; нафтопродукти

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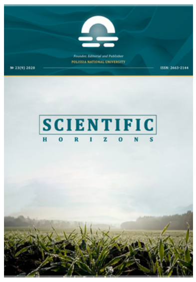

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Implementation of ESG criteria: Integration of environmental, social and governance criteria of companies in water management

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Abstract. In today's environment, achieving sustainable development goals is an important component for any state. In this regard, finding new opportunities to improve the situation in the context of this situation remains relevant. The purpose of this study was to find an opportunity to use Environmental, Social, Governance (ESG) criteria in companies where water management is an important part of their operations. The main methods used were formal legal and forecasting. The paper describes in some

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detail the role of ESG criteria in achieving various development goals of the country, namely economic, social and environmental ones. The use of this approach also helps to attract more investments for enterprises and, therefore, ensure its more rapid development. In addition, the study emphasized the high role of water management in Azerbaijan, which is why the implementation of ESG criteria is particularly important in the country. The study also showed that there is a global trend towards the formation of a legislative framework in countries aimed at mandatory use of ESG criteria for reporting by enterprises. However, this kind of governance is not actively developed in Azerbaijan. In this regard, the paper describes some recommendations on the formation and implementation of this kind of state policy. In addition, the paper formulates recommendations on how companies should use the implemented ESG criteria and how they should be formed on the basis of international standards. The results obtained in the study form an idea of the implementation of ESG criteria both in general and in the context of water management

Keywords: sustainable development; water resources management; public policy; macroeconomics; use of ESG criteria in the regulatory framework

INTRODUCTION

Sustainable development plays an extremely important role in today's environment. At its core, it is a concept and approach to development that seeks to meet the current needs of the population without compromising the ability of future generations to meet their own needs. Thus, development according to this concept should ensure both economic development and sustainability, as well as the maintenance of a clean environment and a high standard of living. Many countries have set the achievement of sustainable development goals as their priority in the long term, and research on this topic remains extremely important. One of the components of achieving sustainable development goals is water management, i.e. more efficient use of water at various enterprises. There are many reasons for this: improving economic efficiency, increasing productivity at the enterprise, reducing risks. In this regard, it is important to develop more effective approaches to managing this component. Since the use of Environmental, Social, Governance (ESG) criteria can help in this context, it is relevant to conduct a study on the possibilities of their implementation. In this paper, the assessment is based on data from Azerbaijan.

Within the modern economic literature of Azerbaijan, there is not a large enough number of works that would describe the specifics of ESG in the country. Nevertheless, some studies of this kind have been conducted. Quite little time was devoted to the description of the ESG concept and its approaches to improving the level of environmental friendliness of business. The problems of implementing European quality assurance standards (ESG) in Azerbaijani universities were described by I. Juknytė-Petreikienė *et al.* (2019). The researchers described the difficulties that exist in this area and formed approaches to improving the situation based on the experience of academic and administrative staff of Azerbaijani universities. The role of human resources in the context of achieving the sustainable development goals was mentioned in the work of U. Alakbarov *et al.* (2020). As can be seen from the above analysis, ESG criteria are paid rather little attention in the Azerbaijani scientific literature, which makes this study even more relevant. The purpose of this study was to assess the possibilities of implementing ESG criteria in Azerbaijan for water management at enterprises.

The study analysed a number of legal acts. This included information from the Implementing and Delegated Acts on Regulation (EU) 2019/2088 of the European Parliament and of the Council of 27 November 2019 on sustainability-related disclosures in the financial services sector (Text with EEA relevance) (2021), aimed at increasing transparency regarding the impact of financial activities on sustainable development. Information on the UK Corporate Governance Code (2024) was also used, and the approaches described in the United Nations (UN) Principles for Responsible Investment were assessed. In addition, parts of the legislative framework of the Republic of Azerbaijan were analysed, which, although not directly related to ESG criteria, is relevant to ensuring sustainable development in the country: information from the Law of the Republic of Azerbaijan No. 80 "On Nature Protection and Nature Management" (1992); Law of the Republic of Azerbaijan No. 1175-VQ "On Environmental Impact Assessment" (2018) was assessed. For a better understanding of what constitutes ESG criteria, various sources of information were evaluated, but the basis for this was the EU Taxonomy Navigator (2024) text, which, among other things, describes what constitutes ESG criteria. The study also proposed to use the Global Reporting Initiative (GRI) methodology to formulate ESG criteria for Azerbaijani companies. In particular, information was used from the Sustainable Development Report 2022 – GRI Content Index (2024), which is primarily related to the regulation of water resources disclosure.

All the previously described assessments of the regulatory framework study were conducted using the formal legal method. The study also compared the approaches to the use of ESG criteria in the world, with the peculiarities that are specific to Azerbaijan. Estimates of the country's future development based on current data were formed using the forecasting method.

THEORETICAL BASIS FOR STUDYING ESG CRITERIA

ESG criteria is an assessment system used by investors and companies to measure the sustainability and social responsibility of a business. Accordingly, environmental criteria for business impact on the environment include energy use, air emissions, waste management, efficient use of resources and other environmentally related aspects. This includes assessing energy efficiency, the use of renewable energy sources, reducing the consumption of resources (e.g. water, forests, minerals) and increasing the efficiency of their use; it also assesses the level of pollution, air emissions, discharges to water and soil resources, and the availability and use of treatment and emission reduction systems (Park & Jang, 2021; Salerno, 2021). Approaches and technologies aimed at reducing the negative impact on the environment are also assessed, i.e. how the company develops and implements environmentally friendly technologies, products, and services; how the company approaches climate risk mitigation and adaptation to climate change (Chen *et al.*, 2021; Vannoni & Ciotti, 2020). As for assessments related to the financial side, it consists of an analysis of financial management, i.e., an assessment of debt levels, working capital management efficiency, financial performance and risk analysis. In addition, the level of transparency of reporting, including the quality of financial statements, compliance with international reporting standards, long-term financial plans and strategies, as well as the level of openness and accessibility of information to investors and stakeholders, plays an important role in this context.

Assessment of a company's level of innovation and investment, including research and development, investment in new technologies, sustainable practices and strategies to drive innovation and growth, also remains important, along with the existence of a working business model, its competitiveness, diversification of products and services, adaptation to changing market conditions and ability to sustain financial growth (Stanislavsky & Zamlynskyi, 2023). As for governance criteria, they include several aspects that help investors and stakeholders assess the level of transparency, ethics, and effectiveness of governance in a company. With regard to governance criteria, they include a number of aspects that help investors and stakeholders to assess the level of transparency, ethics, and governance effectiveness in the company. This is how the governance structure is assessed, namely the composition and role of the board of directors, the structure and functioning of board committees (e.g. audit committee, remuneration committee), and the distribution of powers between executive and independent directors (Maiti, 2021). In addition, the level of ethical standards and corporate culture in the company is assessed, including the existence and compliance with the code of conduct, mechanisms for monitoring ethical violations, and adherence to the principles of honesty, openness, and trust. The level of ethical standards and corporate culture in the company is also assessed, including the existence and observance of a code of conduct, mechanisms for controlling ethical violations, and adherence to the principles of honesty, openness, and trust. Thus, the ESG approach is quite diverse, although not unified.

The interaction between ESG factors and sustainable development is important and mutually reinforcing. ESG factors and sustainability are linked by the common goals of ensuring long-term economic growth, social well-being and environmental sustainability (Chen & Li, 2024). By their very nature, these ratings can be used by a wide range of people, from government officials to investors, and therefore can be used for different purposes. These may encompass the need to assess the negative impact of a particular company on the environment, to form an understanding of the social risks of a particular company, to assess the investment attractiveness of a company. Thus, these ratings should be able to address a much wider range of issues than is expected from conventional financial statements. Water management itself is a rather complex topic, it is multifaceted (Yasin *et al.*, 2021). As part of it, industrial and agricultural companies should use water more efficiently, including by introducing modern irrigation technologies, ensuring reverse sedimentation for wastewater treatment, and using heat and water exchange systems. Active attention should also be paid to the development and implementation of programmes to reduce water leakage in urban infrastructure. States, in turn, should create special natural areas that are not directly affected by external stimuli, which would help preserve water resources (Adamkulova & Aitbaev, 2024). In fact, there are quite a few such "obligations" on the part of the country's economic entities.

Water management plays a critical role in the sustainable development of Azerbaijan, as the country's water resources, including rivers, lakes and groundwater, are vital for various sectors of the economy, including agriculture, industry, and the energy sector. Azerbaijan faces challenges related to limited water resources and their uneven distribution across the country, making the introduction of modern technologies and water conservation strategies, as well as international cooperation for transboundary water management, particularly important. In addition, infrastructure needs to be developed to prevent water pollution and improve water quality. The ESG concept can partially help with this: since these indicators allow assessing the level of measures taken in the context of the approach to achieving sustainable development goals, it will also allow considering approaches to water management. Companies with the best ESG performance, including in the context of water management, will have more opportunities to attract investment and thus be more competitive in the market.

DEVELOPMENT OF APPROACHES TO THE ASSESSMENT OF ESG CRITERIA

The assessment of water management is indeed used in the evaluation of ESG criteria. The environmental component of ESG criteria includes a wide range of issues related to a company's environmental impact, and water management is an important part of this assessment. The most commonly used assessments include water consumption (the amount of water consumed by the company and the efficiency of water use) and water quality (measures to treat wastewater and minimize pollution of water bodies). Various rating agencies conduct such assessments. Among them are MSCI, Sustainalytics, FTSE Russell and others. These organizations use a variety of methodologies and data sources to assess companies' ESG performance. They collect information from public reports, questionnaires, company data and other sources to provide investors and other stakeholders with a comprehensive understanding of the sustainability and responsibility of companies. However, there are no unified standards for this type of assessment: they are formed on the basis of various international practices (for example, the GRI; Sustainability Accounting Standards Board (SASB) standards and others), or they develop their own criteria that they believe best describe the current situation. The approaches used by the rating agencies to analyse the data are not publicly available, and only the final scores of the companies analysed are made available.

In the framework of this study, it is worth considering one of the approaches to water accounting at the enterprise. Thus, the choice was made to conduct an assessment for GRI standards. The advantages and disadvantages of this approach are shown in Table 1.

***Table 1**. Advantages and disadvantages of GRI standards*

Advantages	Disadvantages
GRI standards are widely recognized and used around the world	GRI standards can be complex and extensive, requiring significant resources and time to implement and comply with
GRI covers all three components of ESG: environmental, social and governance aspects	Despite their flexibility, GRI standards can be too general and universal, which can make it difficult to apply them to specific industries or regions
GRI emphasizes the importance of transparency and stakeholder engagement	Unlike the SASB standards, which emphasize the financially relevant aspects of ESG for various industries, the GRI does not always take this aspect into account sufficiently
The GRI standards are aligned with other international initiatives such as the United Nations Global Compact, the Principles for Responsible Investment and others	Despite the existence of clear guidelines, there is an element of subjectivity in the application of GRI standards: different companies may interpret and apply the standards in different ways, which can make it difficult to compare their reports

***Source:** compiled by the authors*

As can be seen from Table 1, the GRI principles are quite universal in their application; moreover, they are more focused on measuring indicators related to the achievement of sustainability goals. They are also aligned with international initiatives, which means that the use of approaches based on them will be more authoritative in the international context.

According to GRI standards, water management is disclosed in five disclosures: interaction with water as a common resource; management of impacts related to water discharges; water withdrawals; water discharges; and water consumption. It is worth briefly considering the specifics of each of the notes. For example, in the first disclosure, organizations should report on how they interact with water, describing in detail where and how water is abstracted, consumed and discharged. It should also describe the approach used to identify water-related impacts, including the scope, timeframe, and tools or methodologies employed. It should also explain how water-related impacts are managed, including stakeholder engagement and collaboration with suppliers or customers with significant impacts; describe water management goals and objectives and how they align with public policy and local water contexts. In the second disclosure (management of water discharge impacts), which should describe the minimum quality standards for wastewater discharges and how they were determined, including standards for facilities without local discharge requirements, internally developed water quality standards or guidelines, industry standards, and consideration of the profile of the receiving water body. Thus, the first two disclosures should contain quite a bit of information, but it is textual: the standards do not provide clear guidance on what water management indicators should be, but rather encourage companies to describe them and prove that they are indeed appropriate.

The next disclosure (water intake) contains the requirements for disclosure of information on water intake: surface water, groundwater, seawater, produced water and water to third parties. The disclosure must include a breakdown of fresh water (≤1000 mg/l of total dissolved solids) and other water (≤1000 mg/l of total dissolved solids), as well as any other relevant variables. Disclosures on water discharge and consumption have a similar structure (Barbosa *et al.*, 2023; Rau & Yu, 2024). Thus, Azerbaijani companies can use these approaches in their own reporting. However, it is important that each individual enterprise (especially from different sectors) first develops its own performance targets in the context of water management and adheres to them. Auditors, in turn, should check whether they are adequate. Such an approach will allow achieving much more efficient water management at enterprises, as well as will make it possible to improve the country's performance in the context of achieving sustainable development goals.

It is worth noting that many countries are introducing the use of ESG criteria into their regulatory frameworks, requiring their companies to interact with them in one way or another to display information related to sustainable development in their reporting. For example, Implementing and Delegated Acts on Regulation (EU) 2019/2088 of the European Parliament and of the Council of 27 November 2019 on sustainability-related disclosures in the financial services sector (Text with EEA relevance) (2021) requires financial institutions to disclose how they integrate ESG factors into their investment policies and decision-making. In the UK, the UK Corporate Governance Code (2024) was the legislative act responsible for this: it described the provisions relating to ESG risk management, which were periodically updated depending on the situation in the country. It is worth noting, however, that in January 2024, all references to ESG were removed from this act. Thus, after the changes come into force in 2025, ESG criteria will no longer be taken into account by companies when managing their businesses in the UK. There is also an initiative from the United Nations called the UN Principles for Responsible Investment, which provides guidance to investors on how to incorporate ESG factors into their investment decisions and, in general, promotes them by suggesting their implementation in different countries.

There are no legislative acts in Azerbaijan that would describe the specifics of using ESG criteria or force companies to do so. Nevertheless, there are some regulations that describe the principles of achieving sustainable development goals. These include Law of the Republic of Azerbaijan No. 80 "On Nature Protection and Nature Management" (1992), Law of the Republic of Azerbaijan No. 1175-VQ "On Environmental Impact Assessment" (2018); laws related to increasing the efficiency of public administration; as well as a set of laws to support vulnerable groups of the population, for example, Law of the Republic of Azerbaijan No. 360-IQ "On the Protection of Public Health" (1997). Nevertheless, these legislative acts are not related to the formation of the principles of reporting according to ESG criteria. As can be seen from the above analysis, not all countries are actively implementing mandatory implementation of ESG criteria in their countries, despite the fact that many create their own alternatives to them. Nevertheless, Azerbaijan currently does not have any principles for this type of reporting in general: in this regard, it is worth considering the possibility of implementation.

The implementation of ESG approaches can be approached through several integrated steps aimed at ensuring effective and sustainable water management. A good place to start is by developing a comprehensive water management plan, which should include an assessment of current water use, setting measurable goals and creating supportive policies. It is important to conduct a thorough analysis of current water use within the organization to identify areas of high consumption and potential inefficiencies. Clear and achievable targets for reducing water use, improving efficiency and minimizing waste should also be set: these should be specific, measurable, achievable, relevant and time-bound. Company policies should support sustainable water use practices: they should include water conservation guidelines, equipment maintenance protocols, and procedures for quickly fixing leaks and other problems (Khumarova & Mahats, 2023).

An important component of the process of implementing such criteria is the training of high-quality personnel: the training process should be multifaceted, and in cooperation with other organizations to share experience and obtain better results at the end of the training process. At the same time, it is worth pursuing a policy whereby any actions of the company's employees aimed at improving the quality of water management will be encouraged in every possible way. Stakeholders should be regularly informed about the progress of water management initiatives through reports, meetings and internal communications. A separate component in this process is the use of the latest technologies. By using smart sensors to obtain real-time data, it is possible to achieve much better results in managing the main processes at one's enterprise. In addition, the data obtained can help identify patterns, detect leaks and optimize water use. It is also worth investing in technologies that recycle and reuse water within the organization to reduce the need for fresh water, and thus reduce its consumption in general. Old and inefficient equipment should be replaced with modern water-saving alternatives, such as low-flow faucets and irrigation systems (Shuka *et al.*, 2011). Other sources of water can also be used, such as treated rainwater.

In terms of regulations, it is worth ensuring that the company not only meets but exceeds regulatory standards by implementing best practices and conducting regular audits and reviews, and adopting industry best practices for water management, which may include advanced treatment processes, pollution prevention measures and sustainable landscaping. It is also worth conducting regular audits and reviews of water management practices to ensure compliance and identify opportunities for improvement. Publishing regular sustainability reports detailing water management efforts, achievements and future plans can build trust among stakeholders, and it is also effective to consider hiring third-party auditors to review water management practices and provide an objective assessment of the company's performance.

Thus, in today's environment, the use of reporting related not only to the financial results of companies, but also to their success in achieving sustainable development goals remains even more important. This is due to all the benefits it can bring to companies, society, and the state. The study paid special attention to the use of ESG criteria for water management, as this is a very important part of achieving sustainable development goals in Azerbaijan. However, it is worth noting that at the moment, although steps are being taken in the country to introduce the use of such criteria, it has not yet been widely applied. In this regard, the state authorities should facilitate this by either forming an appropriate regulatory framework or by any other means.

EVALUATION OF THE RESULTS OBTAINED VIA GLOBAL APPROACHES

The impact of ESG practices on corporate finance was studied by S. Kim and Z.F. Li (2021). They wrote that the impact of ESG factors was generally positive, despite the difficulties encountered in the assessment process. For example, higher overall ESG scores are associated with higher profitability, especially for companies with larger total assets. With regard to credit risk, it turned out that all ESG factors have an impact on a company's credit ratings. However, this impact can vary significantly depending on certain company indicators, such as its size, industry. The effectiveness of ESG was confirmed in the study by N. Engelhardt *et al.* (2021). The researchers showed that during the COVID-19 pandemic, companies with higher ESG ratings demonstrated better stock performance, higher abnormal returns, and lower idiosyncratic volatility. In this regard, they concluded that for companies, investing in corporate social responsibility pays off in terms of share price performance, making them more resilient in times of market uncertainty. From an investor's perspective, the quality of corporate social responsibility is crucial, especially in countries with low levels of trust or in countries with weaker security regulations and disclosure standards. However, given the short evaluation period, more research in this area is worthwhile in the future. The current study also concluded that the use of ESG criteria in a country can lead to significant positive development results for both the economy as a whole and the economy as a whole. In addition, it has a positive effect due to the fact that it allows achieving better results in the social sphere, as well as in the context of environmental protection. In this regard, the use of such criteria remains important for ensuring more rapid economic development.

The modern role of ESG ratings was considered in the study by S. Abhayawansa and S. Tyagi (2021). The researchers noted that the role of these ratings in the context of financial analysis is expected to increase in the future. This growth may be accompanied by regulation of ESG disclosure, as well as their more active use in investment processes. Nevertheless, according to scientists, this will not resolve the difficulties that are currently observed in the context of the use of these ratings. M.H. Shakily (2021) examined how ESG affects a company's financial risks. Based on quantitative data from 2010 to 2018, the researcher described that the use of indicators can reduce financial risks for oil and gas companies in the long term. In this regard, it can be concluded that investors in general should pay attention to the results of ESG assessments when making their own investment decisions. The current study did not conduct such an assessment; however, it also concluded that investors should pay attention to ESG assessments prepared by certain companies. There are several reasons for this: such companies are generally more responsible in their approach to business and therefore more likely to succeed in the long term. In addition, government authorities often have a better attitude towards them due to their focus on sustainability: this also contributes to their financial stability. In this regard, investors should indeed pay attention to ESG criteria when selecting investment targets.

M.O. Yebenes (2024) also assessed the peculiarities of ESG assessment in his study. The scientist noted that their emergence is generally associated with the evolution of financial accounting, aimed at standardizing the assessment of companies' activities in different countries. The long regulatory process has increased the transparency and consistency of financial reporting, but this is not currently the case in sustainability reporting. Although ESG remains a generally effective form of reporting at the moment, it is not ideal or uniform. Nevertheless, the researcher believes that this approach is quite effective, and, therefore, he recommends that investors use it when making their investment decisions. The current study also noted that one of the important components of ESG criteria is the possibility of their reuse by stakeholders, including investors. They may be interested in investing only in those companies that are committed to achieving sustainable development goals, trying to have as little negative impact on the environment and society as possible. In this regard, the application of ESG criteria remains relevant in Azerbaijan as well: their implementation could help attract foreign investors and thus create new conditions for the development of companies and entire industries. Thus, the formation of a unified legislative framework that would create conditions for the application of this concept may also be relevant.

The need to use ESG approaches for small and medium-sized enterprises (SMEs) was described by M. Evangelos *et al.* (2023). Based on their research, the authors proposed to develop a decision support system specifically designed for SMEs to guide them in prioritizing ESG requirements, formulating strategies and aligning operations with ESG criteria. The researchers believe that this system, with the necessary improvements, can serve as a valuable tool for SMEs to effectively report on ESG results. The current study did not pay much attention to the use of these criteria by SMEs. Nevertheless, it is worth noting that this can be effective both in the context of achieving sustainable development goals and the functioning of such companies. However, it should be borne in mind that this can be problematic for SMEs, as the application and use of ESG criteria are costly for companies, and therefore not all SMEs can afford it.

CONCLUSIONS

Thus, the study has shown that the integration of ESG criteria into business practices represents an important shift towards achieving long-term sustainability and social responsibility. The use of this approach helps to improve the efficiency of enterprises in various areas, allowing them to achieve sustainable development goals more efficiently. While financial transparency and ethical governance are equally important components of ESG criteria (ensuring that companies are not only financially sound, but also operate with integrity and responsibility, building the trust of investors, stakeholders and the wider community), their implementation often has other objectives.

Water management, a critical element of sustainable development, is especially important for countries in the Caucasus-Caspian and Central Asian regions that are affected by climate change and disruptions to regional water cycles, such as Azerbaijan, which can benefit significantly from the application of ESG principles. Efficient water use, modern irrigation technologies, wastewater recycling and reduction of leaks in urban infrastructure are all areas where ESG criteria can lead to significant improvements. The study concluded that companies that excel in these areas are likely to attract more investment, thereby increasing their competitiveness in the marketplace and contributing to broader sustainability goals. The study also described an approach to implementing ESG criteria at Azerbaijani enterprises based on international approaches, as well as opportunities to improve the quality of water management.

This paper has shown that some countries around the world have adopted ESG at the national level, primarily EU member states. Nevertheless, the fact that the UK refuses to further use these approaches may indicate that there are alternative options, probably better than ESG, which is why some countries are ready to use them or develop their own. Azerbaijan does not currently have a regulatory framework for the use of these criteria, but its formation should be an important part of the country's future development, maintaining the ecological balance, and protecting water and soil. It is promising for further research to formulate proposals and approaches to the use of ESG approaches for the management of other components of resources that affect environmental sustainability, in addition to water.

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CONFLICT OF INTEREST

None.

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Впровадження ESG-критеріїв: інтеграція екологічних, соціальних та управлінських критеріїв компаній в управлінні водних ресурсів

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Анотація. У сучасних умовах досягнення цілей сталого розвитку є важливою складовою для будь-якої держави. У зв'язку з цим, знаходження нових можливостей для поліпшення ситуації в контексті даної ситуації залишається актуальним. Метою цього дослідження стало знайти можливість використовувати Environmental, Social, Governance (ESG) критерії в компаніях, у яких важливою частиною функціонування є управління водними ресурсами. Основними методами в роботі стали формально-юридичний та прогнозування. У роботі досить детально було описано роль критеріїв ESG для досягнення різного роду цілей розвитку країни, а саме економічних, соціальних та екологічних. Використання цього підходу також дає змогу залучати більше інвестицій для підприємств, а отже, і забезпечувати більш стрімкий її розвиток. Крім того, в рамках дослідження було зроблено акцент на високій ролі управління водними ресурсами в Азербайджані, у зв'язку з чим у країні особливо важливим є впровадження ESG-критеріїв. У роботі також було показано, що у світі наразі існує тенденція, пов'язана з формуванням законодавчої бази в країнах, спрямованої на обов'язкове використання ESG-критеріїв для формування звітності підприємствами. Проте, подібне на правління не має активного розвитку в Азербайджані. У зв'язку з цим, у роботі описано деякі рекомендації з приводу формування впровадження такого роду державної політики. Крім того, у роботі було сформовано рекомендації щодо того, яким чином компанії мають використовувати впроваджені ESG-критерії та як їх варто формувати на основі міжнародних стандартів. Результати, отримані в рамках дослідження, формують уявлення про впровадження ESG-критеріїв як загалом, так і в контексті управління водними ресурсами

Ключові слова: сталий розвиток; управління водними ресурсами; державна політика; макроекономіка; використання критеріїв ESG у нормативно-правову базу

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Decarbonisation of agricultural technologies in Ukraine in achieving sustainable development goals

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Abstract. The study intended to draw attention to the distinctive aspects of Ukraine's agricultural decarbonisation process to carry out the sustainable development plan. The research methodology included statistical observation, analytical and structural grouping, and forecasting. The study established key areas for future development, assessed the extent to which sustainable agricultural production technologies are implemented in Ukraine, and identified reserves. Decarbonisation, which involves a progressive change in the agricultural sector, was discussed in the strategic progress towards a sustainable climate. The significant level of degradation of agricultural areas and the widespread spread of the "organic food" trend were identified as tangential stimulating factors. The expediency of decarbonisation of agricultural technologies in terms of participation in global climate dynamics was substantiated. The main relevant

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challenges and risks were highlighted, and the level of development of the industrial regulatory framework was studied. An analysis was conducted on the characteristics of the agricultural production management system. The most effective means of putting strategies into practice to encourage investment in the agriculture industry were determined. The study demonstrated how farmers can be effectively motivated financially and organisationally to adopt technologies that emit few or no greenhouse gases into the atmosphere, monitor and manage the load on agricultural landscapes, create a targeted land bank, and guarantee quality standards and safety regulations. The vectorial of improving the algorithms for transforming farming systems towards decarbonisation within the strategy of dynamic development from traditional to sustainable agricultural production is determined. The study established that an effective process of decarbonisation of agricultural production technologies is seen as the basis for intensifying the competitiveness of agricultural production. The study demonstrated how Ukraine's agriculture sector has developed in the modern era should be embodied in the technical re-equipment of production processes and fundamental changes in technological methods and approaches to minimise carbon emissions

Keywords: sustainable land use; carbon emission reduction; agroecosystem; certification; strategic management; monitoring

INTRODUCTION

The destruction of landscapes that have long been involved in intensive agricultural activities, in synergy with irreversible global climate change, is making it necessary to move from exhausting forms of agricultural production to organic and environmentally friendly ones. The global trend in the modern development of the integrated community today is the active fight against the emission of carbon and other greenhouse gases. Most countries have diverse practical platforms to improve the ecological state of agricultural landscapes and actively combat irreversible climate change, most of which provide a comprehensive approach to ecosystems and increase the economic efficiency of the industry. Ukrainian realities are characterised by gradual dynamics towards decarbonisation of most technical and technological solutions, although the dynamics of transformation in the Ukrainian space are not rapid. To achieve sustainable development goals, the issue of Ukraine's rapid growth of decarbonisation agricultural technologies is particularly pertinent to this notion.

The issue of implementing sustainable development goals in agricultural production is reflected in the scientific work of modern scientists. A study of current publications shows that studies mostly focus on finding alternative technological opportunities in the agricultural sector to more intensively promote national agricultural progress towards sustainability and environmental safety. B. Babaniyi *et al.* (2024) addressed the basics of adapting organic farming to conventional agricultural systems, highlighting the relationship with global climate dynamics concerning crop production. The researchers identified the functional and structural elements and basic parameters of environmental monitoring of agricultural landscapes, the criteria for assessing the effectiveness of preventive and regeneration strategies of environmental, managerial and financial orientation to intensify the process of decarbonisation of agricultural production in different regions. Scientists address the environmental and economic efficiency of decarbonisation technologies, while its specifics in countries in crisis and instability remain unaddressed.

J. Brinken *et al.* (2023) addressed the complexities of implementing decarbonised agricultural technologies in a crisis economic environment, with an emphasis on legal regulation and motivation in the field. A. Galinis *et al.* (2021), and D. Kuzmanović (2023) deemed it necessary to invest in innovative projects, apply innovative practices of successful international experience, and establish mechanisms for financing decarbonisation projects. At the same time, the functionality of innovation provision in motivating technology transfer and innovation implementation is explored only fragmentarily by researchers.

A. Panfilova and V. Fedorchuk (2022), V. Pichura *et al.* (2024) detailed in depth how the decarbonisation of agriculture's technological approaches is influencing the process of economic development. The authors underscored the necessity of incorporating cutting-edge biotechnologies, ensuring safe handling and preservation, and modifying technological frameworks to collaboratively attain a zero-carbon agricultural footprint and guarantee the ecological soundness of organic products. However, the issue of effective mechanisms to stimulate the reduction of greenhouse gas emissions in agricultural production remains unresolved, which requires further elaboration and search for optimal solutions.

Thus, the study aimed to draw attention to the distinctive aspects of Ukraine's agricultural decarbonisation process to carry out the sustainable development plan.

MATERIALS AND METHODS

The basic categorical concepts and principles of the phenomenon under study were identified, and a definition of the integrity of management processes in the field of decarbonisation of agricultural production was formed. Using an abstract and logical conceptual approach, the conceptual apparatus was determined, and theoretical generalisations and conclusions were formed.

To pinpoint the precise workings of the object under investigation, statistical observation, comparison, analytical and structural grouping, and forecasting were employed. Utilising statistical observation, generalisable data that accurately represents the attributes of the full range of properties of the event under investigation was obtained. To determine the specifics of the dynamics of the growth of decarbonisation and greening systems in the agricultural sector, the primary indicators of qualitative changes were compared. Proposals for optimising the management system in the examined area were developed, along with aspects of developing zero carbon emission systems within the circularity of economic production processes strategy.

The development of technology aimed at decarbonising agricultural output in Ukraine was analysed and synthesised through strategic vectors. To preserve agricultural landscapes and reduce environmental risks in agricultural production complexes, the study outlined the ideal circumstances and solutions within the framework of an efficient and feasible set of management measures for regional agricultural production systems. Based on sustainable decarbonisation of technical processes and "green" sustainable development, the primary vectors for optimising regional agricultural production systems were determined. The conditions were set, particularly about the idea of Ukraine's post-war recovery and the active subsidy and investment assistance from the integrated global community, for the active and practical application of decarbonisation technology in the country's agriculture management system.

A consistent transition from general abstract informative data on decarbonisation technologies in the agricultural sector to the current state of agricultural activity in Ukraine and the creative potential of organic agriculture was created by going from the abstract to the specific. To assess the dynamics of the current practice of implementing innovative agricultural technologies for decarbonisation and minimising the impact on climate dynamics in Ukraine, statistical data from the Ministry of Agrarian Policy and Food of Ukraine, as well as information provided by the official resources of the Information and Analytical Portal of the Agro-Industrial Complex of Ukraine and the National Research Centre "Institute of Agrarian Economics" were used.

The characteristics, benefits, and efficacy of particular techniques and solutions within the framework of the decarbonisation of the agricultural sector were determined using a methodical manner. Particular attention is given to the need to resolve any obstacles to the efficient implementation of agricultural production plans' decarbonisation in light of the economic realities of developing countries. With an emphasis on environmental safety and economic viability, the study seeks to identify solutions in the contemporary agro-industrial complex. These factors work together to create a system of cyclical, sustainable economic activity in the agricultural sector.

RESULTS

Official statistics show that as of 2021, there were 528 organic producers in Ukraine. In comparison, in 2002, only 31 farms were registered (Ukraine ranks 20th…, 2024). The most rapid growth in quantitative indicators in this regard was characteristic of the period from 2015 to 2019, after which the positive dynamics stopped. As of 2024, 475 certified farms in Ukraine successfully operate intensive ecological methods of agricultural production.

The trends in the number of organic farming businesses in Ukraine between 2002 and 2024 show that the agricultural industry has a large amount of potential in the country's economic system, especially during difficult and unstable periods. The data for 2023 show a slight positive trend, which indicates the adaptability and flexibility of the industry, and the willingness of farmers to transform their farming methods in line with current conditions. An analysis of sectoral characteristics and important benchmarks is required to execute a methodical strategy to decarbonise the agriculture industry in the national Ukrainian area. Ecological decarbonised farming technologies are a complex innovation and production system that requires the development of an algorithm for effective sectoral functioning in terms of proportionality of resource and financial potential and corresponding performance. In addition, an integrated approach requires ensuring an appropriate level of resource potential reproduction and minimising environmental impact.

A closed production cycle must be maintained to apply the concepts of sustainable development to the agriculture sector and the decarbonisation of technological processes. Thus, organic farming should be developed in the strategic direction of regeneration and circular economic processes. To reduce financial costs due to the replacement of traditional technologies with decarbonised ones, it is necessary to introduce a definition of the stabilisation interval required to implement a full range of decarbonisation measures in terms of individualising existing production prerequisites. This strategy requires additional financial and time costs, but it is seen as an inevitable stage in the greening and decarbonisation of agricultural production processes. Agrarian formations working towards decarbonising technologies are characterised by different scales of activity (Organic production in…, 2024). The number of small eco-farms is currently growing, with a priority being given to specialising in organic production and export orientation.

Agricultural producers in Ukraine's diverse agricultural regions need to be driven both financially and organisationally, based on the current state of decarbonisation technology development. The degree to which regional investment programs are implemented and the agricultural producers' willingness to change the management system both have a significant impact. European criteria of sustainable development can be applied thanks to innovative technology capabilities that make the shift from overly intensive farming techniques to innovative biologisation tactics easier. The worldwide community acknowledges these standards as alternate, renewable methods for reducing greenhouse gas emissions in the agriculture industry. Based on the findings of the study carried out by the Mykolaiv National Agrarian University Training and Research Centre, as well as the findings of an analysis of industry publications, the most negative effects of global climate change on organic agricultural production include sharp temperature and weather fluctuations, an increase in the difference between night and day temperatures, intensification of weathering and evaporation of moisture from the soil surface, heterogeneity of precipitation and snowy winters. Climate change affects the resilience of agroecosystems, which is noticeable when conventional crop production is transformed into organic.

Creating environmentally safe zones with a minimum volume of 10-15% is the best preventive measure to reduce the amount of agricultural production areas that are ploughed. This will allow for environmental regeneration (Korkhova *et al.*, 2023). In the context of decarbonisation, greening Ukraine's agriculture has great promise for raising production's degree of economic efficiency. Simultaneously, several administrative, financial, and technical actions, including those carried out at the national level, must be taken for this strategic idea to be implemented practically and effectively (Beillouin *et al.*, 2022). These include giving agricultural producers access to current information about cutting-edge technologies with low greenhouse gas emissions, creating nationally recognised organic quality standards and certification, drawing in both domestic and foreign investment, forming alliances, creating a plan for raising farmer awareness through communication, enhancing agricultural organic policy, and encouraging innovation and research (Ramesh *et al.*, 2019). Despite many associated risks and challenges, decarbonisation technologies for agricultural production in Ukraine have significant potential for advancement, with strong international support and investment.

Market economic processes in the concept of ecologization transform the basic goal of agricultural production, namely, increasing financial profitability and productivity growth. In the agriculture industry, a pertinent management plan is created by the synergistic development of profit and environmental impact. The main goal of the latter is to intensify productivity and sustainability in a complex of interrelated organisational and information tools, levers and principles. The proposed approach will improve the competitiveness of agricultural enterprises. The following should be emphasised as some of the most crucial elements of the system of requirements for putting the plan for the development of decarbonisation of agricultural output into practice (Kovalenko *et al.*, 2024):

- scientific and legislative (awareness of the norms and requirements of the Ukrainian legal framework and the ability to predict and model potential legislative changes in the industry, as well as the study of foreign experience, are the primary prerequisites for the effective development and implementation of strategic innovations);
- technological and technical (the adoption of the newest creative methods, technologies, and concepts based on a preliminary study of statistical data and financial and economic information is a necessity for sustained progress towards decarbonisation of agricultural technology);
- human resources (regional development potential is based on an awareness of local needs and resources, considering the specifics of the communication process between farmers and territorial governments).

Among the basic concepts of strategic management of farm productivity in the direction of decarbonisation are systematic, efficient, flexible, balanced, risk minimisation, and others (Table 1).

***Table 1**. Concepts of strategic management of decarbonisation of agricultural technologies in Ukraine*

No.	Principle	Meaning
1	Adaptability	Variability of the dynamics of the algorithm for implementing management strategies under the influence of exogenous and endogenous factors
2	Possibility of implementation	Identification of strategic goals of the organisation's development includes consideration of its resource potential to assess the possibility of their implementation
3	Structuredness	The process of decarbonisation project management should have a structure, regulations and an individual algorithm for practical implementation
4	Prospectivity	Focus on long-term perspective development of the agricultural sector
5	Economic effect	Implementation of decarbonisation measures should be financially viable
6	Monitoring	Management measures should ensure the controllability of decarbonisation processes with a system of control indicators
7	Systematic approach	Decarbonisation covers all aspects of the organisational activities to achieve the overall goal

***Source:** compiled by the authors based on T. Ramesh et al. (2019) and E. Durán-Lara et al. (2020)*

Given its substantial resource potential for active growth, the agricultural sector is considered one of the top priorities for economic national development. Agricultural enterprises are currently positioned as a small form of entrepreneurship, and therefore have significant advantages, including a simplified process of implementation into the market environment, increased adaptability of the economic activity process due to small production scales, and a quick response to market dynamics (Gamajunova *et al.*, 2021; Kazimierczuk *et al.*, 2023). Small agricultural producers have advantages over other agricultural entities in terms of the decarbonisation process, as savings on on-farm transport, management costs, and an interest in improving operational efficiency contribute to the successful development of the agricultural segment. Because of the existing circumstances in Ukraine, it is necessary to optimise the legal and methodological framework and put into action workable steps to increase their profitability and competitiveness (Zelisko *et al.*, 2024).

It is worth noting that agricultural production is a sector highly dependent on the combined impact of natural and climatic factors. Sometimes, even their timely forecasting is not able to prevent the risks of unprofitable agricultural activities. The approach of modelling production processes in the whole set of interdependencies and elements of influence should serve as the foundation for the perspective vectors of the agricultural sector development. Figure 1 displays the overall decarbonisation strategy management algorithm for the agriculture industry.

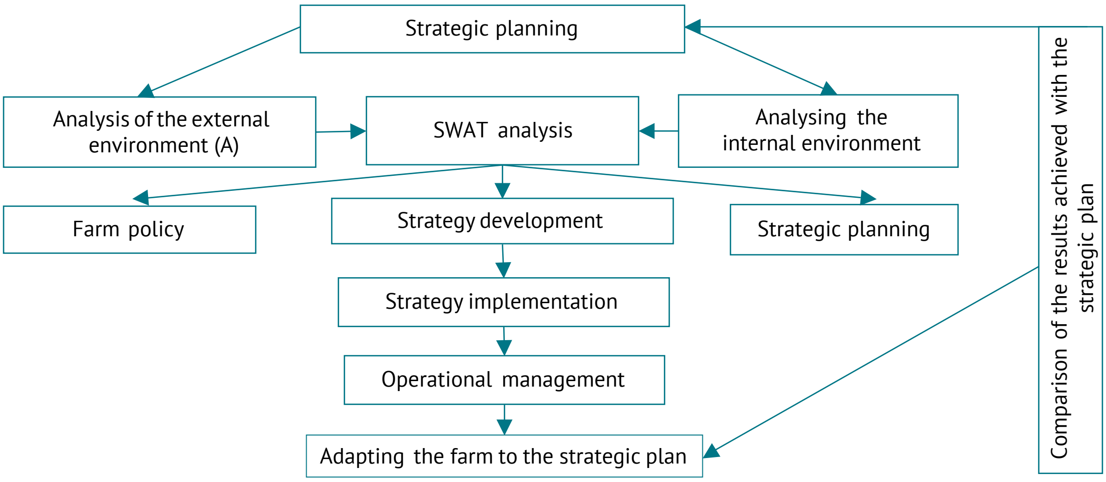

***Figure 1**. Algorithm of management strategy for decarbonisation of agricultural technologies in Ukraine*
***Source:** compiled by the authors based on T. Ramesh et al. (2019), E. Durán-Lara et al. (2020), R. Sroufe and A. Watts (2022)*

The decarbonisation of agricultural production can be achieved through the integration of systemicity and alternative concepts, together with proactive risk prevention. These approaches will work in concert to promote the expansion of agricultural production's economic efficiency. It makes it possible for agriculture to advance via technological innovation and environmental sustainability, encouraging investments in updated equipment and the use of sustainable development ideas in the agricultural industry. Modernisation also implies the use of research and development opportunities in practice, which directly affects the growth of the export potential of agricultural production.

Implementing advances in agriculture happens in phases: scientific solution – technology – production – consumption. The implementation algorithm directly depends on a set of features of the agricultural sector regional and functional, financial, social and managerial, and other factors. The pace of agricultural modernisation depends on some of these factors, including the availability of innovative infrastructure, which determines the level of integration, readiness to implement functional changes, and resource potential. To decarbonise the agricultural sector, technological advancements must intensify resource use's energy efficiency. This can be achieved by breeding, precision agriculture, innovative equipment and technological system optimisation, breeding, and the organic chemicalisation of agricultural processes, among other key strategic decisions (Holmes *et al.*, 2021; Soofi *et al.*, 2022). Today, modern bioenergy strategies are gaining popularity as an additional area of technological modernisation towards zero carbon emissions. This strategy is the most appropriate in the current economic environment, given the priority of the principles of sustainable development in all areas of production, including agriculture.

To effectively execute a methodical strategy for optimising the decarbonisation of Ukraine's agricultural industry, it is imperative to tackle the sector's particularities as well as the standards that constitute an exemplar of productive agriculture. Decarbonisation of agricultural technology is defined as a complex of production modernisation, the management of which, to be effective, necessitates taking into account metrics related to resource potential, the particulars of sectoral functioning, and the assurance of adequate reproduction processes. It is necessary to guarantee an agricultural production cycle that is technologically closed to adhere to the principles of sustainable development. Decarbonisation should be implemented in the form of practical reproduction algorithms, considering the existing influencing factors, in particular, production, material and technical, organisational, economic, environmental and social. The innovative technology for decarbonising the agricultural sector involves identifying reliable field characteristics, using GPS technology tools, and drawing up electronic maps. The difference between modern technologies in agricultural production is the absence of destructive impact on the environment, preservation of soil fertility and obtaining environmentally friendly products by following an algorithm of a set of safe biotechnological techniques. A separate aspect is to ensure zero or minimal emissions of carbon and other greenhouse gases that cause global climate change.

The process of gathering, accumulating, and analysing information data is the foundation for developing eco-technologies, making effective management decisions, and modifying the schemes of agricultural production processes. This is how the strategic concept of implementing decarbonisation technologies in the agricultural sector to achieve circular economic processes and sustainable development goals is based (Fig. 2).

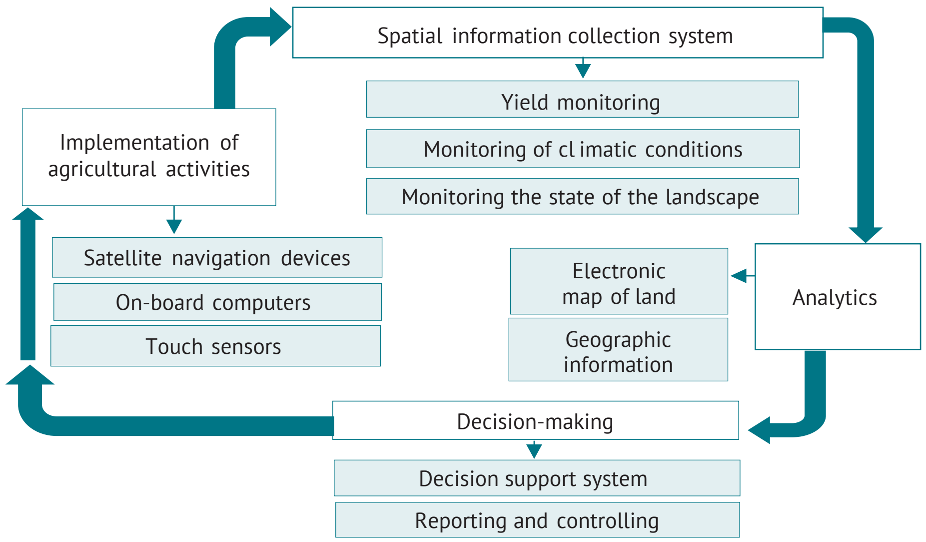

***Figure 2**. Components of the implementation system of agricultural decarbonisation systems*
***Source:** compiled by the authors based on T. Ramesh et al. (2019), E. Durán-Lara et al. (2020), R. Sroufe and A. Watts (2022)*

To assess the economic efficiency of implementing modern decarbonisation technologies, in addition to the traditional indicators of payback and profitability, yield growth and productivity, and annual economic effect per unit area, metrics for reducing the impact of climate change are also used, which are determined from informative data on the qualitative and quantitative composition of carbon emissions into the environment.

Further potential study in this area should be devoted to the identification of strategic vectors for creating a stable system of agricultural consulting on decarbonisation, integration of information support and environmental monitoring systems, which in synergy constitute the main resource for optimising the situation. At the same time, the priority function is to attract foreign practical successful experience and develop and improve a comprehensive multifactorial approach to managing farm productivity. Together with efficient management practices and an agricultural-environmental monitoring system, the implementation of the system of target requirements in the context of the maximum environmental impact, bringing current agricultural production standards into compliance with developed country standards, and implementing cutting-edge, innovative technological approaches to agricultural processes based on a closed cycle of resource use optimise the Ukrainian agricultural sector. Further research is needed on the possibilities of expanding the use of geoinformation technologies, using the potential of innovative navigation and mapping devices, as well as agroecological monitoring systems. The recommended course of action can be used to develop a state-of-the-art management decision support system that will guarantee food security, promote sustainable development in the direction of greening and decarbonising agricultural technologies, and significantly improve the productivity of the country's agricultural sector.

DISCUSSION

Modern technological modernisation of agriculture towards decarbonisation is focused on innovative optimisation of agricultural production towards decarbonisation. The strategy provides for the provision of material and technical resources, organisation of production activities following the modern requirements of international industry standards, and effective management of information flows, innovations and technological processes towards sustainable development. Regulatory and legal support for agricultural reforms, environmental protection and diversification, together with innovative technological modernisation of agricultural production, can guarantee favourable preconditions for the most efficient development of sustainable agriculture in Ukraine.

Modern research confirms the fact of economic inexpediency and the extremely negative impact of exhausting traditional methods of agricultural production on the environment, given the intense negative climate dynamics (Shuvar & Korpita, 2023). According to M. Singh (2021), agricultural modernisation should align with the green economic development course's aims as it represents a progressive shift from conventional to technological production. This sentence is notable since it represents the primary scientific hypothesis of the study. M. Singh states that the level of modernisation can be used as a metric of the effectiveness of the practical use of research and development. According to the research of F. Eyhorn *et al.* (2019), actively forms an innovative organisational and managerial algorithm of activity in the agricultural sector. According to M. Diacono *et al.* (2019), the need for trained workers in the local area, the marketing of scientific research, and intense urbanisation are the long-term effects of these processes. The majority of contemporary scientists believe that organic farming systems built on decarbonisation technologies are essential to the long-term health of the ecological network supporting agricultural production. This network serves as the foundation for efficient resource regeneration and wise resource allocation within the agricultural sector within the framework of reorienting economic processes towards sustainability, renewability, and circularity.

M. Krauss *et al.* (2020), in a study on management support for decarbonisation processes as the main prerequisite for intensifying the productivity of the agricultural sector, demonstrate that the system of biological land use and decarbonisation of agricultural technologies has significantly expanded the boundaries of practical implementation, becoming a concept for representing the desired sustainability of future agricultural production. In the absence of proper preventive measures, the researchers stress that the dynamics of conventional agricultural processes are moving towards ecologization, and this is accompanied by a major shift of socio-economic processes that are destabilising. The primary objective of the process of decarbonising agricultural production is to control the balance between production and the natural environment to minimise the detrimental effects of human activity on the quality of the nearby natural resources and climate stability.

The primary objective of decarbonising agricultural technologies, according to A. Le Campion *et al.* (2020), is to create sustainable agroecosystems with the ability to self-ameliorate and mitigate the adverse consequences of climate change. The researchers analyse the component and functional structure of a typical algorithm for environmentally friendly production with minimal emissions of carbon and other greenhouse gases, noting the need to expand the boundaries of the technological potential of innovative agricultural strategies and highlighting the need for intensive sectoral investment. It should be noted that the idea of renewability is now regarded as a crucial component of agricultural-landscape complexes that are sustainable. It guarantees a suitable degree of natural environment component regeneration that can operate well without requiring a substantial amount of financial subsidies (Tanchyk *et al.*, 2024).

The synergy between the decarbonisation of agricultural technologies and sustainable development goals was actualised by A. Gamage *et al.* (2023). Decarbonising agricultural production technology improves important environmental metrics like air quality and the dynamics of the global climate while balancing the socioeconomic balance of business and society. The researchers also the importance of applying sustainable management principles to the agricultural sector and the associated issues, including those about the financing and investment system and the availability of trained individuals. Comparing the results of this study with the conclusions reached by scientists, it is important to keep in mind that, as Ukraine rebuilds itself after the war, it is becoming more likely to attract focused investment opportunities and international cooperation mechanisms, which will significantly increase the range of workable agricultural-environmental solutions.

T. Clunies-Ross and G. Cox (2023), in continuation of the problem, focuses scientific attention on the priority of closed-loop technologies in agricultural production, which minimise the environmental impact of the agro-industrial complex, contributing to the sustainable development of the industry. Scientists argue that today the agricultural sector needs large-scale support in the form of investment and lending aimed at maintaining agricultural landscapes, reducing greenhouse gas emissions and preventing climate change. Numerous contemporary scientists, including S. Parizad and S. Bera (2023), contend that integrated management in agricultural production will enable the successful resolution of strategic tasks like resource optimisation, enhancing the sustainability of agricultural-ecological systems, superior monitoring, and efficient handling of environmental risk situations. Limiting activities that cause chemical and other hazardous contamination of natural resources and their deterioration, as well as efficiently controlling the impact of agricultural production processes, are important to minimise the detrimental influence on the environment (Havryliuk *et al.*, 2022).

A priority area for optimising the industry's circumstances is, according to G. Wu *et al.* (2020), the establishment of an efficient system of managerial and financial incentives at the national, regional, and local levels to promote the use of decarbonisation projects. Sustainable development incentive programmes should include subsidies and benefits for active participants in the process of decarbonising production. Such a management strategy's anticipated long-term outcomes were detailed by J. Pombo-Romero and O. Rúas-Barrosa (2022) include the improvement of the social and environmental microclimate, the improvement of the living environment and the growth of the economic efficiency of innovative projects. According to M. Ouikhalfan *et al.* (2022), the establishment of a mechanism for state support for agricultural innovations, farmer motivational policies, the organisation of a unified investment system, and the global integration of the network of agricultural innovation transfer centres are some of the driving forces behind the successful technological modernisation of the agricultural sector.

Summarising the results of the work of modern authors and the conclusions drawn in this paper, it is possible to identify the specifics of the technological modernisation of agriculture in the direction of decarbonisation and minimisation of the impact on global climate change. Primarily, the adoption of technical breakthroughs boosts the competitiveness of agricultural production by increasing the productivity and economic efficiency of agricultural activities. C. Granjou *et al.* (2024) share this position. At the same time, modernisation creates a shortage of qualified personnel and the need to develop scientific potential. When agricultural output is successfully optimised, the agricultural sector's export potential will increase and both domestic and international investment will be drawn in. After analysing and summarising the foregoing, the prognostic viewpoint calls for extending the decarbonisation technologies' functionality within the management policy strategy of Ukraine's agricultural sector. This will considerably boost the sector's productivity and introduce safe management practices that adhere to the principles of sustainable green development.

Therefore, enhancing the productivity of farming businesses and guaranteeing steady food security can only be achieved by a well-balanced approach to automation and mechanisation, as well as through technologically optimising fundamental production processes that adhere to the principles of sustainable agriculture. A successful technical modernisation process will complete the transition to a creative growth model, reduce detrimental processes in agricultural landscapes, and increase production efficiency.

CONCLUSIONS

The implementation of decarbonisation in agricultural technologies in Ukraine ought to be achieved by optimising the sector's management policy in terms of priority. To achieve sustainable development goals, an analysis of the key elements of Ukraine's issue with the decarbonisation of agricultural technologies reveals several inter-sectoral gaps that must be immediately closed through sectoral regulatory and legal regulation, the application of international greening industry principles and standards, the drawing of international investment levers, and the establishment of stringent liability measures. To effectively manage contemporary agroecosystems in the context of preventing climate change and decarbonisation, a coordinated effort is needed to improve the systems' functionality, efficiency, and capacity for regeneration. For the agricultural sector to optimise its management paradigm, the system of strategic planning, operational management, effective regeneration, and preventive measures are considered to be the most important factors. A strategy like this will offer the best way to address emerging issues, such as changing agricultural practices to better reflect the dynamics of the global climate.

The progressive replacement of conventional, labour-intensive agricultural processes with intensive ones founded on the ideas of sustainable development and the green economy should be the main focus of Ukraine's agricultural sector's technological modernisation towards decarbonisation and sustainable development. The study supports the necessity for national regulatory frameworks to incorporate the international experience of decarbonising the agriculture industry and to encourage innovation, investment processes, and the financial and organisational incentives of agricultural producers. These strategic measures, employed together, form the optimal prerequisites for solving current problems in the field of agricultural production. Based on the ideas of diversification and production process rationalisation, the study finds the most viable methods for the decarbonisation of agricultural technologies. According to the study, the only way to considerably reduce environmental impacts and boost agricultural production efficiency is to apply managerial, economic, and technological measures in concert with the introduction of novel monitoring techniques.

Prospects for research include the formation of strategic vectors for decarbonising the agricultural sector in different regions of Ukraine. To analyse and address the issues facing the business, a workable procedure for combining cutting-edge agricultural and environmental monitoring skills must also be established. Active involvement of international experience, development and implementation of innovative management methods in the agricultural sector based on regeneration and sustainable land use, and improvement of institutional frameworks are seen as necessary preconditions for Ukraine post-war regeneration and European integration.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Декарбонізація аграрних технологій в Україні у контексті досягнення цілей сталого розвитку

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Анотація. Дослідження спрямоване на виокремлення специфічних рис аграрної декарбонізації в Україні в межах реалізації стратегії стійкого розвитку. Методологія дослідження передбачала використання методів статистичного спостереження, аналітично-структурного групування та прогнозування. У дослідженні визначено рівень імплементації технологій стійкого сільськогосподарського виробництва в Україні, ідентифіковано існуючі резерви, сформовано пріоритетні напрями перспективного поступу. Поступова трансформація аграрного сектору в концепті декарбонізації розглядається в статті у контексті пріоритетності стратегічного поступу в напрямку стійкого клімату. Дотичними стимулюючими факторами визначено значний рівень деградації аграрних територій та масштабне поширення тренду «organic food». Обґрунтовано доцільність декарбонізації аграрних технологій у аспекті участі в глобальній динаміці клімату. Виділено основні дотичні виклики та ризики, вивчено рівень розвитку галузевої нормативно-правової бази. Проаналізовано особливості системи управління у галузі сільськогосподарського виробництва. Визначено пріоритетні шляхи імплементації методологій стимулювання інвестування у аграрну сферу. Доведено доцільність дієвої фінансової та організаційної мотивації аграріїв щодо впровадження технологій з мінімальним чи нульовим викидом парникових газів у атмосферне повітря, моніторингу та контролінгу навантаження на агроландшафти, формуванні цільового земельного банку, забезпеченні стандартів якості та вимог безпеки. Визначено векторність вдосконалення алгоритмів трансформації систем землеробства у напрямку декарбонізації в межах стратегії динамічного розвитку від традиційного до стійкого аграрного виробництва. Встановлено, що ефективний процес декарбонізації технологій аграрного виробництва вбачається основою інтенсифікації конкурентоспроможності сільськогосподарського виробництва. У дослідженні вдалося довести, що сучасний розвиток галузі аграрного виробництва в Україні повинен знаходити втілення у технічному переоснащенні виробничих процесів та фундаментальній зміні технологічних прийомів та підходів задля мінімізації емісії вуглецю

Ключові слова: стійке землекористування; зменшення емісії вуглецю; агроекосистема; сертифікація; стратегічний менеджмент; моніторинг

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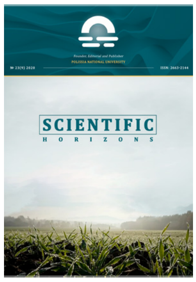

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Entrepreneurial characteristic effect on business performance of millennial farmers

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Abstract. The Indonesian agricultural sector still has considerable potential for growth, but this is not currently being realised due to a lack of adequately trained human resources, particularly among the younger generation. It is anticipated that the younger generation will assume leadership roles within this sector. However, there is a dearth of interest among this demographic in pursuing careers in this field. The issue can be addressed by fostering an entrepreneurial mindset among millennial farmers. Therefore, the purpose of this study was to determine the entrepreneurial characteristic effect

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on millennial farmers' business performance. Data were obtained through in-depth interviews and observations using a questionnaire. Additionally, the sample size was 120 millennial farmers in Central Java within ten selected regencies. Snowball sampling was determined based on data from millennial farmers designated as ambassadors by the Ministry of Agriculture and data analysis used Partial Least Square Structural Equation Modelling (PLS-SEM). The results showed that the business performance of millennial farmers was measured based on four key indicators: turnover, source of capital financing, production capacity, and marketing reach. The findings indicated that entrepreneurial characteristics, as measured by individual features, risk-taking courage, and self-confidence, had a positive and significant effect on business performance. In this context, the business performance of millennial farmers could be enhanced by leveraging their individual characteristics, including a strong commitment, a mature evaluation of risk, and high confidence in their capabilities. Individual characteristics play a pivotal role in business performance. To build their brand in developing businesses, millennial farmers receive capacity-building training

Keywords: farmer regeneration; networking; role model; leadership; risk-taking

INTRODUCTION

In Indonesia, the agricultural sector is reported to have the largest number of workers compared to others with a total of 40.63 million people in 2023 (Central Agency of Statistics, 2023). This shows that the sector is the largest contributor to employment national economy and plays a significant role in the national economy. In 2020–2024, it has been directed to practice advanced, modern, and independent agriculture. As indicated by the agricultural extension and human resource development agency, the government has established a series of pivotal objectives pertaining to agricultural advancement. These include the objective of fostering the emergence of 2.5 million millennial entrepreneurs by the year 2024. Concurrently, the agricultural sector is confronting a series of challenges, including a shortage of young farmers. The proportion of individuals under the age of 35 engaged in agricultural work has declined significantly, from 24.53% in 2021 to 20.02% in 2023. (Central Agency of Statistics, 2023). This decline shows a lack of interest and understanding among the younger generation regarding pursuing a career in this sector. It is therefore vital to implement strategies aimed at regenerating the farming community to ensure the long-term sustainability of the food supply. One potential solution is to cultivate entrepreneurial skills among the younger generation.

The term "entrepreneurship" is defined as the capacity to generate novel ideas and solutions through creative thinking, with the aim of capitalising on opportunities for success. Entrepreneurial characteristics encompass the attributes, dispositions, and actions of an entrepreneur that facilitate the utilisation of creativity, innovation, and the capacity to leverage existing opportunities for enhanced business performance (Andjarwati *et al.*, 2021). The agricultural sector is facing a series of challenges, including the issue of farmer regeneration. The perception that agriculture is not a viable business opportunity has resulted in a significant decline in the number of young people pursuing careers in this field. In contrast, E. Riptanti *et al.* (2024) argue that the future sustainability of food security is contingent upon the regeneration of farmers. Considering the data from the Central Agency of Statistics (2023), a decline in the number of young people employed in the sector becomes clear. In 2011, the figure stood at 29.18%, declining to 19.18% in 2021. This decline suggests that young people have a low interest in, and unfavourable perceptions of, working in the sector (Zulu *et al.*, 2021).

The Indonesian province of Central Java is endowed with considerable agricultural potential. In 2022, the Central Java Provincial Statistics Agency recorded a total of 2,979,396 individuals aged 15 years and over engaged in primary employment within the agriculture, forestry, and fisheries sectors (Central Java Provincial Statistics Agency, 2023). Notably, one-third of these farmers are millennials. A. Murtagh *et al.* (2023) noted that various initiatives have been implemented to address the challenge of regeneration. These include efforts to engage the interest and awareness of the younger generation in pursuing a career in agriculture with a focus on the role of millennial farmers.

Millennial farmers can adapt to digital information technology to create innovation and improve quality, productivity, and competitiveness in agriculture. It is expected that the advent of the millennial farmer will engender innovation and enhance the quality, productivity, and competitiveness of agriculture. E. Riptanti *et al.* (2024) noted that in the context of innovation, successful farmers should possess robust entrepreneurial characteristics to achieve optimal farm performance. Concurrently, business performance is contingent upon a multitude of datasets for a variety of purposes. According to F. Kitsios and E. Grigoroudis (2020) and S. Chen *et al.* (2020), the success of on-farm farming is contingent upon not only the practices employed on the farm itself, but also the competencies of the actors involved in the agricultural business. These competencies encompass attitudes, knowledge, and skills.

The entrepreneurial characteristics of an individual are manifested in their personality traits, human resources, and business track record. According to A. Titien (2021), these include several aspects, namely individual attributes, leadership capabilities, the capacity to take calculated risks, self-assurance, and the proclivity for networking. The issue of regeneration in agriculture is a considerable challenge that must be addressed to ensure the future viability of this sector. Apart from its role in food security, agriculture can become a major contributor to the national economy. It is therefore essential to develop a mindset among young farmers that encourages entrepreneurial spirit and the pursuit of a decent standard of living. A plethora of characteristics are associated with successful entrepreneurs, including self-confidence, individual characteristics, the capacity to accept calculated risks, leadership and a dynamic spirit, the ability to build networks, creativity and flexibility, and the spirit of optimism. An effective business management system is contingent upon a robust entrepreneurial mindset. R. Astuti *et al*. (2024) mentioned that millennial farmers need an entrepreneurial spirit which provides benefits in the form of economic independence and mental fortitude in running business. According to T. Chandrayanti *et al*. (2020), entrepreneurial characteristics affect business performance of an entrepreneur.

Based on these problems, the influence of entrepreneurial characteristics on the business performance of millennial farmers in Central Java Province needs to be investigated. The findings are anticipated to inform the formulation of government policies designed to foster an entrepreneurial spirit among millennial farmers. Consequently, the purpose of this study was to ascertain the impact of entrepreneurial attributes on the business performance of millennial farmers.

MATERIALS AND METHODS

The study employed a quantitative approach to test certain theories by investigating the relationship between variables. The study was conducted between April and August 2023. The location was selected purposively, namely the Central Java Province, considering the province's potential for the agricultural sector and the number of millennial farmers, which constituted 33.7% of the 2.88 million in Central Java. The sample of locations was selected from ten regencies with the highest concentration of millennial farmer representatives, as designated by the Decree of the Ministry of Agriculture. These included Magelang, Sukoharjo, Klaten, Wonosobo, Tegal, Purbalingga, Temanggung, Semarang, Purworejo, and Banyumas.

A combination of purposive and snowball sampling was employed to select the sample of millennial farmers. The inclusion criteria were that the farmers must be aged between 19 and 39 years old and must be in charge of businesses in one or more of the following sectors: food agriculture, horticulture, fisheries, animal husbandry, and plantations, with activities spanning from upstream to downstream. The study employed six latent variables, reflected in 24 indicators, to measure the sample of 120 respondents (Hair *et al.*, 2019). The categories of variables and indicators used are presented in Table 1.

Table 1. *Categories of variables and indicators used*

Variable	Source	Indicator	Symbol
Individual Characteristic (IC)	P. Nguyen *et al.* (2023); T. Katz-Gerro *et al.* (2024)	*Cosmopolite*	IC1
		Education	IC2
		Experience	IC3
		Creativity	IC4
Leadership (L)	V. Srimulyani *et al.* (2023); I.N. Persada and S.D. Nabella (2023)	*Role model*	L1
		Motivator	L2
		Treatment of employees	L3
		Goal-oriented	L4
Risk-Taking Courage (RTC)	L. Mozumdar *et al.* (2022)	*Risks to develop the business*	RTC1
		Risks to innovate	RTC2
		Risks to achieve goals	RTC3
		Basis for retreat	RTC4
Self-Confidence (SC)	I. Otache *et al.* (2021)	*Entrepreneurial skills*	SC1
		Self-organisation	SC2
		Initiative	SC3
		Optimism	SC4
Networking Capability (NC)	S. Pattanayak *et al.* (2024); F. Sadeh and M. Kacker (2020)	*Expanding of network*	NC1
		Networking capabilities	NC2
		Trust preservation	NC3
		Relationship-building skills	NC4
Business Performance (BP)	H. Cuevas-Vargas *et al.* (2023); M. Latifi *et al.* (2021)	*Sales growth*	BP1
		Profit growth	BP2
		Modal growth	BP3
		Market growth	BP4

Source: *compiled by the authors of this study based on the findings of researchers cited in Table 1*

The data were collected via a questionnaire administered through face-to-face interviews. The millennial farmers who took part in the study were willing to provide their identities. Data has been analysed through the PLS-SEM approach. This technique explored the relationship between various variables in a model (Hair *et al.*, 2019). The questionnaire was tested for validation and reliability before being used for data collection (Sürücü & Maslakçi, 2020). Validity was proven by the Average Variance Extracted (AVE) value and Composite Reliability (CR) on reliability, while instrument testing used 30 respondent data. The study was conducted following the Declaration of Helsinki (2013).

A PLS-SEM analysis was conducted in two stages, namely outer and inner models. The outer model comprised two tests: a validity test and a reliability test. The validity test entailed an examination of the convergent and discriminant validity of the indicators, whereas the reliability test employed Cronbach's Alpha (CA) and Composite Reliability (CR). Inner model analysis was evaluated through two indicators, namely the coefficient of determination (R^2) and predictive relevance (Q^2), while the hypothesis was performed using bootstrap resampling.

RESULTS AND DISCUSSION

Business Performance of Millennial Farmers in Central Java Province. Business performance describes the success of a business operated by an entrepreneur. This can be evaluated using indicators of profit and sales volume (Lytvynenko *et al.*, 2022). In parallel, the evaluation encompasses a synthesis of internal and external factors within an organisational context. The SWOT analysis is subdivided into two distinct categories: external and internal factors. The internal factors within the SWOT analysis comprise strengths and weaknesses, whereas the external factors encompass opportunities and threats. The indicators can be quantified through the measurement of sales growth, capital growth, marketing strategies, and profit improvement. (Cuevas-Vargas *et al.*, 2023). The business performance of millennial farmers is reflected through four key indicators: the level of turnover generated, production capacity, capital in business, and increased market coverage. Based on the amount of turnover per month, these farmers have already achieved a turnover of over 5 million per month, representing 66.33% of the total. Approximately 29.16% of respondents have a high turnover, which is equal to or greater than IDR25 million per month. The production capacity in Central Java Province is heterogeneous due to the diverse range of business types. The production capacity is classified as good and has a positive impact on business turnover, demonstrating a direct proportional relationship between the two variables.

Most of the initial business capital (85%) was sourced from personal funds, while the remainder was obtained through bank loans. H. Yang *et al.* (2021) mentioned that increased capital is directly and positively proportional to the income received. Most marketing outreach activities were directed towards local and national markets, representing 45.83% and 39.17% of the total, respectively. According to M. Latifi (2021), an expansion in growth suggests an enhancement in the operational efficiency of a business.

Analysis of the Entrepreneurial Characteristics Effect on Business Performance. The PLS-SEM analysis method is conducted in two stages: the outer and inner models. The aim of the outer model is to specify the relationship between latent variables and their indicators. The inner model is used to determine the relationship between the latent variables. Prior to the analysis of the data, the study instrument was subjected to validity and reliability tests using data from 30 respondents. The results of the research demonstrate that this construct exhibits an AVE value exceeding 0.5 and a CR value exceeding 0.7. Consequently, the instrument was considered both valid and reliable (Hair, 2019). However, two indicators, namely IC4 and RTC4, were identified as invalid.

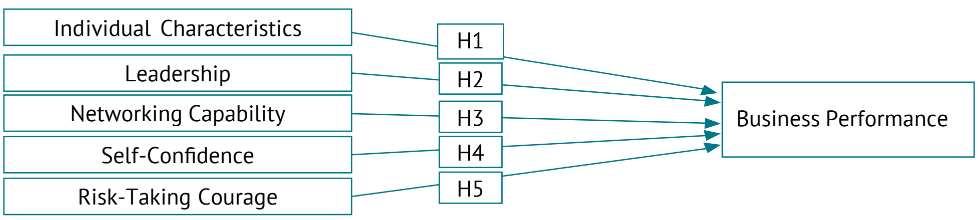

***Figure 1**. Study Model*
***Source:** adapted by the authors of this study from Wei et al. (2023)*

Outer Model Evaluation. The evaluation of the outer or measurement model begins with the assessment of convergent validity (CV), discriminant validity (DV), and reliability tests. The convergent validity (CV) test is assessed using two indicators: the Loading Factor value and the Average Variance Extracted (AVE) value, which is presented in Table 5. Each indicator demonstrates a factor loading value of 0.7 or above and an AVE value of 0.5 or above. These results suggest that the data is valid, and thus the model meets the CV requirements, as all indicators represent latent variables. The outer model evaluation is presented in Table 2.

***Table 2.** Outer model evaluation*

Variable	Indicator	*Loading factor*	*AVE*	*CA*	*CR*
Business Performance (BP)	BP1	0.812	0.614	0.790	0.864
	BP2	0.799			
	BP3	0.740			
	BP4	0.782			
Individual Characteristic (IC)	IC1	0.836	0.662	0.742	0.854
	IC2	0.869			
	IC3	0.731			
Leadership (L)	L1	0.708	0.584	0.762	0.849
	L2	0.748			
	L3	0.806			
	L4	0.792			
Networking Capability (NC)	NC1	0.785	0.591	0.773	0.852
	NC2	0.824			
	NC3	0.730			
	NC4	0.732			
Risk-Taking Courage (RTC)	RTC1	0.859	0.696	0.785	0.873
	RTC2	0.861			
	RTC3	0.780			
Self-Confidence (SC)	SC1	0.712	0.552	0.731	0.831
	SC2	0.753			
	SC3	0.792			
	SC4	0.711			

***Source:** compiled by the authors of this study based on the findings of researchers cited in Table 1*

The results of the reliability test demonstrate that all constructs or variables employed have CA and CR values exceeding 0.6 and 0.7, respectively. Therefore, the variables are reliable, providing consistent and stable answers (Zheng *et al.,* 2023). In this context, the study variable is employed in the subsequent test, namely structural model evaluation. The results of the DV test are based on the Fornell-Larcker value and cross-loading. The Fornell-Larcker value demonstrates that the square root of the AVE is greater than the correlation value of the latent variables, thereby confirming the validity of the results. Furthermore, the cross-loading value of each indicator on related constructs is higher than that on unrelated constructs, indicating a stronger correlation between the indicator and the construct in question. Table 3 presents the Fornell-Larcker value results for the outer model evaluation.

***Table 3.** Fornell-Larcker value in outer model evaluation*

	BP	IC	L	NC	RTC	SC
BP	**0.784**					
IC	0.430	**0.814**				
L	0.342	0.498	**0.764**			
NC	0.379	0.325	0.437	**0.769**		
RTC	0.448	0.385	0.563	0.445	**0.834**	
SC	0.487	0.388	0.561	0.521	0.617	**0.743**

***Source:** Central Java Provincial Statistics Agency (2023)*

Inner Model Evaluation. The evaluation of the inner model is based on the R^2 and Q^2 values. The R^2 value indicates a result of 0.336, which is categorised as moderate. This value demonstrates that 33.6% of business performance can be explained by entrepreneurial characteristics variables, including individual characteristics, leadership, networking capability, risk-taking courage, and self-confidence. The Q^2 value of 0.186 indicates predictive relevance, and the path model is deemed to be effective for predicting the observed values.

Hypothesis Test. Hypothesis testing employs the bootstrapping method, whereby the theoretical correlation between exogenous and endogenous variables is evaluated through path analysis (Anizar *et al.*, 2021). This study employed a 95% confidence level, or a value of <0.05, and the hypothesis was considered significant upon meeting the requisite criteria at the 5% significance level, namely a p-value <0.05 and a t-statistic >1.96. The relationship between exogenous and endogenous variables was organised into a structural model: $BP = \alpha + \beta 1\ IC + \beta 2\ L + \beta 3\ RTC + \beta 4\ SC + \beta 5\ NC + e$. The hypothesis test results are presented in Table 4.

***Table 4**. T-statistic values and p-values on hypothesis testing*

Hypothesis	Correlation	*Path Coefficient*	*p-values*
H1	IC → BP	0.265	0.003^{***}
H2	L → BP	-0.090	0.362^{ns}
H3	NC → BP	0.114	0.217^{ns}
H4	RTC → BP	0.184	0.035^{**}
H5	SC → BP	0.262	0.009^{***}

***Notes:** ns – not significant; *** – significant at $\alpha \leqslant 1\%$; ** – significant at $\alpha \leqslant 5\%$*
***Source:** Primary Data Analysis (2024)*

H1: It is suspected that individual characteristics affect millennial farmers' business performance. Based on Table 4, hypothesis **H1** is **accepted,** and this is in line with S. Nabilah *et al.* (2022), where individual characteristics significantly affect business performance. The cognitive abilities of millennial farmers are characterised by a strong capacity for study and analysis of business operations. According to S. Nabilah *et al.* (2022), individual characteristics, such as a strong commitment, exemplary conduct, and a foundation of education and knowledge, serve as a form of trust capital, facilitating enhanced business performance. This is influenced by an indicator of individual characteristics, namely the dimensions of age, education level, and experience, which serve as sources of strength to encourage business actors to develop businesses. The majority of millennial farmers have completed secondary education and graduated from university, which increases their ability to understand information and marketing trends.

The process of developing character among millennial farmers involves the sharing and training of activities that are appropriate to the fields in question. Some of these farmers possess the creativity to produce innovative products, which is reflected in the product characteristics or marketing methods employed. According to V. Graskemper *et al.* (2020), the implementation of creative strategies at the level of the millennial farmer can result in the development of more diverse business strategies. The innovative products produced by millennial farmers include processed gethuk brownies derived from cassava, dried crystal guava bakpia, probiotic coffee, and ornamental plants used for souvenir packaging. The introduction of these innovative products can enhance marketing, which can lead to an increase in sales turnover.

H2: It is suspected that leadership affects millennial farmers' business performance. Hypothesis **H2** is **rejected** based on data from Table 4 and this result is in line with H. Mwakajila and R. Nyello (2021), where leadership style does not significantly affect business performance. This finding is also consistent with the results of the study conducted by M. Jony *et al.* (2019), which indicated that there is no significant correlation between leadership style and performance. However, some studies contradict these findings, namely M. Gofur *et al.* (2021), where the development of business performance is positively influenced by leadership. There is considerable diversity in leadership styles, with millennial farmers serving as role models to inspire, motivate, and listen to employees. As K. Folarin (2021) has observed, the leadership of the millennial generation represents a significant challenge due to the distinct approaches they bring to the table.

H3: It is suspected that networking capability affects millennial farmers' business performance. Hypothesis **H3** is **rejected** based on the data presented in Table 4, where networking capability does not affect millennial farmers' business performance in Central Java Province. This result is in line with R. Kurniawan *et al.* (2021), where networking capability has no direct effect on business process capabilities. According to R. Rustianah *et al.* (2023), networking capability affects business performance. E. Riptanti *et al.* (2022) highlighted the significance of networking capability in forming partnerships with other businesspeople. This capability is highly diverse, encompassing a range of aspects, from the scope of the network to the main source of capital and the patterns formed within it.

Despite their commitment to building business networks, millennial farmers still face considerable challenges in realising their commitments. This is conditioned by a series of factors, including limited access provided by partners and binding regulations from business partners. Furthermore, most farmers market their products in a limited scope without adequate networking capability. According to E. Riptanti *et al.* (2022), several networks affiliated with the production input supply subsystem include local farmers and breeders, companies that produce seeds, companies supplying raw materials from outside the region, as well as farmer groups and joint ventures.

A further innovation in the study was the incorporation of the expanding network indicator within the capability variable, which proved unable to elucidate the impact on business performance. Some millennial farmers encounter difficulties in establishing relationships with partners due to disparate priorities. A case in point is the relationship between tobacco farmers and cigarette companies. Millennial farmers with limited marketing coverage have not maximised the presence of technology to expand business network. Some only use WhatsApp for two-way communication and have not expanded to other social media to develop networking capabilities.

H4: It is suspected that risk-taking courage affects millennial farmers' business performance. Based on Table 4, **H4** was **accepted**. M. Suder (2022) supported the results where risk-taking had a positive and significant effect on business performance. The willingness and ability to take risks is a significant aspect of entrepreneurial orientation. Entrepreneurs who are reluctant to take risks tend to be less inclined to initiate new ventures. However, it is essential for them to be able to navigate risk and uncertainty effectively. Nevertheless, excessive risk-taking can also have adverse effects on business performance. Some entrepreneurs may be inclined to avoid risks and favour strategies that have a proven track record of generating expected profits.

The confidence that millennial farmers possess enables them to take risks to develop their businesses. This confidence is based on careful evaluation. According to L. Mozumdar *et al.* (2022), some risks should be faced to achieve success. It is often observed that high-risk-taking leads to increased returns, and thus this variable is frequently associated with business success. The results of in-depth interviews with millennial farmers indicate that the majority have experienced repeated business failures. These experiences are viewed as opportunities for learning and avoiding similar mistakes or risks. Millennial farmers demonstrate a willingness to embrace new business ventures, as evidenced by their production of fertilizer under the RASSELabmix label for horticultural crops. This fertilizer has been successfully marketed in Central Java and the Special Region of Yogyakarta (DIY).

H5: It is suspected that self-confidence affects millennial farmers' business performance. Hypothesis **H5** is **accepted** based on the data presented in Table 4, where self-confidence significantly affects business performance. According to E. Riptanti *et al.* (2024), self-confidence has a positive effect on business success and serves as a driving factor for entrepreneurs in innovating. The confidence of millennial farmers is reflected in the success of the businesses they run. Additionally, some demonstrate initiative and an optimistic outlook regarding business progress. According to R. Ryan *et al.* (2021), individuals who demonstrate high capability tend to exhibit motivation in terms of effort, perseverance, and behaviour, in comparison to those who evince pessimism. Millennial farmers demonstrate a high level of confidence in their ability to effectively manage time, resources, and teams, thereby maximizing business potential. Initiatives undertaken by grape farmers in Magelang, who are members of the "Gemblung farmer" community, involve the development of new grape varieties. This is achieved using a homemade laboratory for conducting crossbreeding trials involving a range of varieties.

CONCLUSIONS

In conclusion, the business performance of millennial farmers was reflected in four key indicators: turnover, production capacity, capital in business, and increased market coverage. The variables of individual characteristics, risk-taking courage, and self-confidence were found to have a positive effect on business performance, while leadership and networking capability did not. Therefore, the indicators of individual characteristics, risk-taking courage and self-confidence should be considered as potential avenues for improving business performance.

The business performance of millennial farmers was found to be influenced by a range of individual characteristics, including self-confidence and risk-taking courage. The effect of individual characteristics on business performance was found to be explained by indicators of cosmopolitanism, education, and experience. Furthermore, entrepreneurial ability, self-management, initiative, and optimism were identified as factors influencing the effect of self-confidence on business performance. The courage to take risks, as reflected in the indicators of risk to business development, innovation and achievement, also explained the effect of the variable on performance. In this context, government programmes should pay attention to business performance based on the effect of the three variables. Millennial farmers felt confident in their abilities and skills by managing time and resources to improve business potential. Additionally, business performance in the good category showed that sustainability was efficiently maintained and developed.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Вплив підприємницьких характеристик на ефективність бізнесу фермерів-міленіалів

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Анотація. Сільськогосподарський сектор Індонезії все ще має потенціал, але він не збалансований з відповідними людськими ресурсами, особливо наступним поколінням. Очікується, що молоде покоління стане наступником, але насправді воно має низький інтерес до цього сектору. Подолання проблеми можливе шляхом зміни мислення фермерів-міленіалів через розвиток у них підприємницьких якостей. Тому метою цього дослідження було визначити вплив підприємницьких характеристик на ефективність бізнесу фермерів-міленіалів. Дані були отримані шляхом проведення глибинних інтерв'ю та спостережень за допомогою анкетування. Крім того, розмір вибірки склав 120 фермерів-міленіалів у Центральній Яві в десяти обраних регіонах. Вибірка за методом снігової кулі була визначена на основі даних від фермерів-міленіалів, призначених послами Міністерством сільського господарства, а для аналізу даних використовувалося моделювання структурних рівнянь методом найменших квадратів (PLS-SEM). Результати показали, що ефективність бізнесу фермерів-міленіалів вимірюється на основі чотирьох показників, а саме: оборот, джерело фінансування капіталу, виробничі потужності та охоплення ринку збуту. Підприємницькі характеристики через змінні індивідуальних особливостей, сміливість у прийнятті ризиків та впевненість у собі мали позитивний і значний вплив на ефективність бізнесу. У цьому контексті ефективність бізнесу може бути покращена за допомогою індивідуальних характеристик фермерів-міленіалів, таких як сильна прихильність, зріла оцінка ризику та висока впевненість у своїх можливостях. Індивідуальні характеристики відіграють домінуючу роль у результативності бізнесу. Фермери-міленіали проходять тренінги з розбудови потенціалу для створення брендингу в бізнесі, що розвивається

Ключові слова: відродження фермерства; мережування; рольова модель; лідерство; прийняття ризиків

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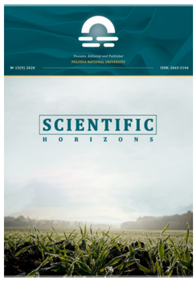

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The current state and prospects for the use of organic acids and their compositions in poultry feed: A literature review

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Abstract. The use of antibiotics in poultry farming is critically limited, which leads to the search for and research of alternative compounds to replace antibiotics. Organic acids are considered one such alternative, but the antimicrobial and metabolic effects of fatty acid blends are still controversial and understudied. All this necessitates a systematic analysis of the current data on effective antibiotic replacement strategies. The purpose of this study was to analyse and summarise current ideas on the use of organic acid mixtures as an alternative strategy for sustainable poultry production. An analysis of current literature showed that one of the most promising alternatives to the use of antibiotics in poultry farming is mixtures of organic acids and their derivatives, which have antibacterial effects, lower pH, are involved in energy metabolism, and all this together contributes to intestinal function. Organic acids have a positive effect on physiological functions, namely, digestion and the immune system, are the main source of energy for colonocytes, and reduce the pathogenic bacterial load on the digestive tract. Mixtures of organic acids were shown to be more effective than their individual use, specifically, mixtures of short- and medium-chain fatty acids were shown to be highly effective in supporting the intestinal barrier, microbiome, and immunity, with the former acting better as growth promoters and the latter having higher antibacterial

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properties. The efficiency of organic acids alone or in mixtures depends on many factors, depending on the type of molecule, form, and dose. The expediency of further studies of the effects of organic acids was substantiated, which will be useful for the development of antibiotic-free strategies using the synergistic effects of their mixtures and multidirectional cytoprotective effect. The findings of this study will be useful for scientists and veterinarians to learn about the prospects of using organic acid compositions as antibiotic alternatives, specifically for the development of technological approaches to minimise their use

Keywords: blends of short-chain and medium-chain fatty acids; poultry farming; antibiotics; intestinal function maintenance

INTRODUCTION

Poultry farming is the most widespread form of livestock production in the world, due to its relatively low cost and short production cycle. At the current stage of poultry development, the best possible conditions have been created to fulfil the genetic potential of animals. According to N. Haulisah *et al.* (2021), one of the key methods of increasing broiler productivity since the 1950s has been the use of antibiotics as growth promoters (GPs). However, the use of these substances has brought the issue of antibiotic resistance to a new level that threatens humanity. The most widely used antibiotics, as GPs, have been used to improve feed conversion and health status of poultry (Salah *et al.*, 2019). The abandonment of antibiotics has initiated an increase in the number of studies on effective alternative methods of monitoring and correcting animal health, welfare and productivity, including in poultry farming.

A wide range of products have been proposed to replace antibiotics in feed, among which organic acids (OAs) show promising results (Mantzios *et al.*, 2023). The pool of carboxylic acids that are most common in living organisms is represented by free fatty acids and those that are part of the lipids of living organisms. According to D. Venegas *et al.* (2019), according to the chain length, fatty acids are divided into short-chain fatty acids (SCFAs) – containing up to 6 carbon atoms, medium-chain fatty acids (MCFAs) – containing 6-12 carbon atoms, and long-chain fatty acids (LCFAs) – containing 13-21 carbon atoms. There is also elongated chain fatty acids (VLCFAs), which have over 22 carbon atoms. All SCFAs have varying degrees of water solubility, which distinguishes them from LCFAs, which are insoluble. In the poultry industry, SCFAs are used more frequently and somewhat less frequently than MCFAs as an alternative to antibacterial preparations and growth stimulants. G. Galli *et al.* (2021) note that the effectiveness of SCFAs and MCFAs is influenced by a considerable number of factors, among which the key ones are the chemical structure, form of additive, its amount and method of supplementation, buffer capacity of feed, and its nutritional value.

Organic acids are widely used as additives in drinking water or as feed additives (acidifiers). They are often used in the salt forms (sodium, potassium, or calcium and/or partially esterified). According to M. Aljumaah *et al.* (2020), the advantage of using salts is their odourlessness, solid form (the purest organic salts are volatile), lower corrosivity, and better solubility. The efficiency of an organic acid depends on its molecular weight, pKa value and form (undissociated or dissociated), which together determine the difference in antimicrobial activity and bioavailability. Several OAs have a specific bioavailability. The bioavailability of OAs can be improved by choosing the correct form of additive that promotes OA adsorption by cells. F. Mannelli *et al.* (2019), N. Qi *et al.* (2023) pointed out that the use of fatty acid salts is the simplest solution, as these salts are solid, which facilitates the technology of feed production and improves their organoleptic properties. Microencapsulation is considered a promising way to deliver organic acids to the digestive tract. Therewith, the composition of the coating that envelops the OA ensures a more efficient release of these substances in the right place in the digestive tract.

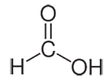
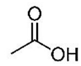
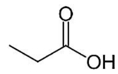
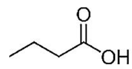
The purpose of this study was to summarise the current comprehension and prospects for the use of short- and medium-chain organic acids in poultry farming as safe substitutes for antimicrobial agents and/or growth promoters based on the analysis of available literature.

APPLICATION OF SCFAS IN POULTRY FARMING

OAs are organic compounds with acidic properties, the most common of which are carboxylic acids, whose acidity is related to their carboxylic group – COOH. These acids are weak, partially dissociated and have a pKa (pH at which the acid is half dissociated) of 3 to 5. SCFAs used in poultry production include oil, vinegar, propionic, dairy, formic, apple, wine, fumaric, and sorbic (Ricke *et al.*, 2020). SCFAs (acetate, propionate, and butyrate) are produced by bacterial fermentation in the intestine and have certain effects on metabolism and the immune system. Apart from being important cross-nutrition products, microbial metabolites also have a positive effect on the mucous membrane of the digestive tract. SCFAs play an important role in the metabolic and immune homeostasis of the digestive tract, as well as in the integrity of the intestinal barrier, which opens great opportunities for therapeutic development (Venegas *et al.*, 2019).

The intestinal microbiota releases SCFAs (mainly acetate, propionate, and butyrate) in the colon during fermentation, from where they are absorbed by the colon epithelium through passive and active transport. The pathways of formation of various SCFAs and the corresponding microbial producers were identified. The products of microbial fermentation of SCFAs are the main source of energy for colonocytes (Deleu *et al.*, 2021). At the same time, all commensal gut taxa ferment pyruvate to produce butyrate, while pathogenic bacteria, such as Fusobacterium, use different pathways, such as glutamate (4-aminobutyrate) and lysine, which are associated with the release of harmful by-products, such as ammonia. The key factors that limit the production of SCFAs in the digestive tract include pH, growth factors, and gas levels. Carbohydrates, which lead to high production of SCFAs, lower the pH in the colon, which affects the microbial composition and production of SCFAs. The availability of growth factors such as iron is crucial for the production of SCFAs. Significantly lower concentrations of butyrate and propionate were found in the faeces of iron-deficient rats. Iron deficiency induces an increase in the number of Lactobacilli and Enterobacteriaceae species and, conversely, a decrease in *Roseburia* and *Eubacterium rectale* species, which are the main producers of butyrate. Oxygen and Hydrogen levels affect the fermentation process and the production of SCFAs (Louis & Flint, 2017). Overall, only 4 SCFAs are currently widely used in poultry production (Table 1).

***Table 1**. Short-chain fatty acids used in poultry production*

Name		Formula		Mass (g/mol)	Diagram
Common	Systematic	Molecular	Structural		
Formic acid	Methanoic acid	CH_2O_2	H–C(=O)–O–H	46.0	
Acetic acid	Ethanoic acid	$C_2H_4O_2$	CH_3COOH	60.1	
Propionic acid	Propanoic acid	$C_3H_6O_2$	CH_3CH_2COOH	74.1	
Butyric acid	Butanoic acid	$C_4H_8O_2$	$CH_3(CH_2)_2COOH$	88.1	

***Source:** compiled by the authors of this study based on the literature data*

Acetic, butyric, and propionic acids are the most abundant SCFAs in the colon, where they have a positive effect on energy status by providing a carbon source for the intestinal microbiota through the activation of glyoxylate pathway enzymes. In commercial poultry production, SCFAs are mainly associated with antimicrobial activity and increased productivity (Scicutella *et al.*, 2021). The antimicrobial effect of propionic and butyric acids is conditioned by the acid dissociation constant (pKa = 3 – 5). Once in the intestine, they lower the pH, which inhibits potentially pathogenic bacteria, and increase the level of calcium, phosphorus, and magnesium in the blood serum due to improved absorption (Us *et al.*, 2017).

Lactic acid is used in poultry production both in pure form and in the form of butyrates, coated/encapsulated (lipid-coated) butyrate salts (Nguyen *et al.*, 2020) and butyrate glycerols (butyrine). Each product formulation has its own advantages and limitations in terms of bioavailability, cost, biosafety, stability, processing temperature/pressure, and digestive release. The use of an encapsulated form of lactic acid in laying hens showed better results than butyrate.

Butyric acid is one of the main acids that are successfully used in industrial poultry farming. This acid modulates the state of symbiotic microbiota and improves immunological homeostasis in the intestine. Butyrates (calcium or sodium salts) are easily converted to butyric acid in the digestive tract and are considered safe. Compared to other MCFAs, butyrate has a slight antibacterial effect, but is not expensive. The use of butyrate reduces the concentration of total circulating triglycerides and cholesterol in broilers (Khatibjoo *et al.*, 2018). Sodium butyrate is the most common form of butyric acid. There is a number of studies showing that the addition of butyric acid, in various doses, from 0.2 g/kg to 0.6 g/kg, to broiler chickens' diets improves performance, digestibility, and nutrient absorption, and reduces the incidence of disease. The mechanism of butyrate effect is that when sodium butyrate enters the stomach, it releases the Na ion (Gao *et al.*, 2022). Due to the low pH, butyrate is rapidly converted to the undissociated form of butyric acid (Elnesr *et al.*, 2020).

Butyric acid is formed by microbial fermentation in the colon and is the main source of energy for colonocytes, affects their proliferation, differentiation, gene expression, and protein synthesis, and improves its absorption. Butyric acid reduces bacterial colonisation of the intestinal wall by lowering the pH, which reduces the tendency to diarrhoea. The addition of butyric acid or butyric acid glycerides to turkey diets was shown to have a beneficial effect on feed conversion, intestinal morphology, and bird health by reducing pathogen concentrations in faeces (Makowski *et al.*, 2022). The use of feed additives based on butyric acid inhibits the spread of Salmonella infection and contamination of bedding with pathogens.

The addition of 0.5% acetic, lactic, or formic acid to drinking water limits the growth of *S. Typhimurium* in chickens (El-Saadony *et al.*, 2022). However, sublethal concentrations of undissociated acetic acid may not always stimulate the acid resistance of *Salmonella enterica sub*. enterica serovar *Enteritidis Phage* (Gavriil *et al.*, 2020). A relatively new area is the use of dietary fermented fibres to produce bioactive fatty acids in the intestines of animals (Ali *et al.*, 2022). The addition of 1% wheat bran with a particle size of 280 μm to the feed leads to its rapid fermentation in the digestive tract with the formation of butyric acid. These feed additives improve the performance of broiler chickens. Glycerol monolaurate is successfully used in poultry feeding, which not only improves meat quality, but also has antibacterial properties at a dose of 300 mg/kg against *Escherichia coli* and *Eimeria spp*. (Fortuoso *et al.*, 2019). The expressed antimicrobial effect of LCFAs formed as a result of fermentation of cranberry processing waste was shown. The beneficial effect of high doses of α-linolenic acid (21.0%) and linoleic acid (39.7%) obtained from fermentation products was aimed at preventing encephalomalacia, improving the immune response against infectious bursal disease virus (IBDV) and Newcastle disease (Islam *et al.*, 2020).

EFFECT OF SCFA ON METABOLISM AND IMMUNE DEFENCE

SCFAs are transported through the basolateral mucosa of the colon to the portal bloodstream, probably with the participation of SCFA-specific receptors. SCFA receptors, which are activated by acetate and propionate, were found on intestinal endocrine L cells. The GPR 109A receptor, which is expressed by colon epithelial cells, is activated by butyrate and provides IL10 production and an anti-inflammatory response. The OLFR 78 receptor is expressed in renal blood vessels and is involved in blood pressure regulation (Kotlo *et al.*, 2020). Despite a considerable amount of information on the effect of SCFAs on metabolism and energy homeostasis, the mechanisms of transport and biological activity of SCFAs are still understudied.

Along with the studied protective effects, there is an evidence of the damaging effect of butyrate on the intestinal barrier in the inflammation presence (Vancamelbeke *et al.*, 2019). Comparable results were obtained regarding the protection of colon stem cells from microbial metabolites. Some studies have shown conflicting data on the positive effect of butyrate on the intestinal barrier. For instance, butyrate promotes the growth of SCFA-producing bacteria in patients with digestive disorders (Facchin *et al.*, 2020). Oral administration of butyrate to mice aggravated colitis, while its intraperitoneal administration improved the animal health. On the other hand, inhibition of butyrate-producing microorganisms caused an exacerbation of colitis in mice. Acetate supplementation in mice plays a crucial role in the intestinal response to tissue damage and repair in colitis (Laffin *et al.*, 2019). Undoubtedly, further study is needed on both microbiome-derived and dietary-supplemented SCFAs pool to applicate SCFAs in digestive tract diseases. Despite the aforementioned data, the use of SCFAs for therapeutic purposes, their optimal therapeutic doses and indications for the use of SCFA-producing bacteria or SCFAs are still unresolved.

In vitro studies have provided evidence of the beneficial effects of butyrate on the intestinal barrier. Butyrate contributes to the Butyrate contributes to the intestinal barrier integrity by activating genes whose products maintain transepithelial electrical resistance (TEER). Butyrate has been shown to stimulate the energy metabolism of intestinal epithelial cells, modulate the production of hypoxia inducible factor 1 (HIF-1) and transcription factors, which together support the intestinal barrier function. Particularly important are the results of SCFAs' impact on the intestinal barrier and the immune system. SCFAs can modulate the adaptive immune system by stimulating macrophages and dendritic cells. SCFAs can initiate the transformation of naïve T cells into regulatory T cells (Oliveira *et al.*, 2018). Apart from polarising regulatory T cells, SCFAs also affect the polarisation and activation of Th1, Th2, and Th17 cells by inhibiting histone deacetylase (HDAC). Acetate, propionate, and butyrate also promote Th1 and Th17 differentiation in vitro. HDAC inhibition by butyrate and propionate promotes IFN-γ expression, which enhances antiviral immunity (Luu *et al.*, 2018).

The effect of SCFAs on certain types of immune cells (neutrophils, monocytes, and macrophages) is also achieved through a decrease in histone deacetylase (HDAC) levels (Ratajczak *et al.*, 2019). The effects of SCFA on cytokine transcription are conditioned by the activation of the nuclear factor kappa B cell (NF-κB). Thus, SCFAs are involved in the regulation of cellular response genes expression to damage, including infectious agents. Stimulation of cytokine production is a universal mechanism that ensures an adequate cellular response. In this response, it is critical to ensure a balance between pro- and anti-inflammatory factors. The ability of SCFAs to regulate anti-inflammatory cytokines and pro-inflammatory cytokines including IL-1β, IL-6, IL-8, and IFN-γ was found in broilers and piglets (Wu *et al.*, 2018). Furthermore, SCFAs affect neutrophil chemotaxis induced by inflammatory mediators. SCFAs can affect the differentiation and function of dendritic cells, specifically, in vitro studies showed butyrate inhibiting their maturation during incubation with various inflammatory inducers.

In addition to their regulatory effects, SCFAs are a complete source of energy for enterocytes. The content of SCFAs in the chicken caecum varies according to the content of the dominant microbiota (Cuccato *et al.*, 2021). Microbiota modification with antibiotics in mice showed a strong association between SCFAs content and the number of Bacteroides in the caecum. Elevated concentrations of SCFAs are considered beneficial for gut health by lowering pH and inhibiting pathogens. However, too high SCFAs content can inhibit beneficial taxa together with pathogens. This undesirable effect of organic acids supplementation to the diet reduces feed intake and inhibits weight gain in broiler chickens.

SCFAs inhibit cholesterol synthesis by inhibiting the activity of the enzymes 3-hydroxy-3-methylglutaryl-CoA synthase (HMGCS) and 3-hydroxy-3-methylglutaryl-CoA reductase (HMGCR). Thus, SCFAs are involved in the indirect regulation of energy metabolism by modulating cholesterol-dependent hormone synthesis and lipid metabolism. Another way in which SCFAs are involved in metabolic regulation is by reducing plasma glucose levels through the activation of the fatty acid receptors Ffar2 and Ffar3. The lack of butyrate-producing bacteria in the microbiome induced a decrease in FFAR2/3 receptor signalling, suppressed mucin formation, and increased intestinal permeability (Mishra *et al.*, 2024). Considering all the above-mentioned data, the use of SCFAs in poultry production requires a detailed comprehension of the protective mechanisms in the intestinal system cells as well as the possible risks of inhibiting intestinal function.

USE OF MEDIUM-CHAIN FATTY ACIDS

Medium-chain fatty acids (MCFAs) are considered a promising alternative to antibiotics due to their beneficial effects on digestion. MCFAs exhibit antibacterial activity, activate absorption, inhibit lipase production by bacteria and have a lower ability to dissociate (Dierick *et al.*, 2002). The mechanisms of action of MCFA are still unclear. MCFAs can act as non-ionic surfactants, incorporating into the bacterial double layer of lipids to form pores, leading to a critical increase in permeability and cell destruction. MCFAs are rapidly absorbed in the small intestine, transported to the liver as free fatty acids, and enter the mitochondria independently of fatty acyl-CoA carnitine transferases (Roopashree *et al.*, 2021). The administration of MCFAs reduces lipogenesis, lipid uptake, fatty acid biosynthesis, and increases their oxidation.

It is assumed that the antibacterial efficacy of MCFAs is comparable to that of SCFAs, but their mechanism of impact is different in respect to that of SCFAs. MCFAs have a pKa value of about 4.9 and their efficiency decreases with molecular weight magnification. An important feature of MCFAs is their ability to easily penetrate dense peptidoglycan (Gram+ bacteria) and/or phospholipid (Gram- bacteria) membranes in undissociated form (Hermans *et al.*, 2010). The MCFAs adsorbed by the cells dissociate in the protoplasm, lowering the pH, which initiates critical damage to microbial cells. This property of MCFAs makes them promising substitutes for antibiotics, especially against gram-positive cocci and *Escherichia coli*. Campylobacter spp. infections cause an estimated 250,000 cases of gastroenteritis in the EU and a cost of over EUR 2.4 billion annually (The European Union One Health 2018; Zoonoses Report, 2019). Despite the widespread occurrence of *Campylobacter* in warm-blooded animals, the main source of infection is birds, specifically broiler chickens (Peh *et al.*, 2020). Addition of MCFAs to the feed for 3 days reduces Campylobacter colonisation in 27-day-old broilers experimentally infected with *C. jejuni* at 15 days of age. Feed additives with MCFA significantly reduce *Campylobacter* carriage in broiler chickens.

MCFAs, namely caproic, caprylic, and capric acids, are digested and absorbed faster than long-chain fatty acids, improve digestion, absorption, and lipid transport. Furthermore, MCFAs prevent the adsorption of bacteria to the intestinal wall and reduce invasion by inhibiting the production of bacterial lipases. The beneficial effect of MCFAs (C6-C12) alone and their mixture with SCFAs (C2-C6) was shown in respect to performance, carcass characteristics, haematological and biochemical parameters of broiler chickens' serum. Monoglycerides synthesised using MCFAs are also considered as a promising alternative. Recently, the results of their beneficial effects on performance, intestinal histomorphology, amino acid digestibility, and blood chemistry of broiler chickens have been presented. A metagenomic analysis of organic acid use has shown a stimulating effect on the diversity of beneficial microorganisms, nutrient digestion, and muscle growth (Dauksiene *et al.*, 2021).

APPLICATION OF ORGANIC ACID MIXTURES IN POULTRY FARMING

Numerous studies on feed additives applying have shown that mixtures of organic acids (two or more) have significantly better efficacy than any one acid alone (Szabó *et al.*, 2023). Specifically, SCFAs enhances the antimicrobial effect of MCFAs, which supports the gut microbiota of piglets and feed conversion in laying hens. The polymodal effects of a mixture of fumaric, citric, malic acids with capric and caprylic acids on productivity, Lactobacillus content, IgG concentration and inhibition of E. coli growth were shown. The mixture of phosphoric acid (0.2 g/kg) and lactic acid (0.3 g/kg) increases the pH of the pectoralis major and thigh muscle within 24 hours. The use of a mixture of microencapsulated organic acids with MCFAs has a positive effect on egg production, egg strength, calcium concentration, and the content of *Lactobacillus* and *E. coli* in the faeces of laying hens.

There is a fairly considerable number of results showing the beneficial effect of organic acid mixtures on the intestinal function and health of productive poultry. Specifically, the use of mixtures of butyric, fumaric, and lactic acids in different proportions had a positive effect on poultry body weight gain, feed conversion rate, and increase in the height of villi in the small intestine. A positive effect of sodium butyrate supplementation with MCFAs salts on the intestinal health of broiler chickens has been shown (Sadurní *et al.*, 2022). The addition of SCFAs and MCFAs to the broiler diet reduces serum cholesterol levels, abdominal fat, and thigh fat percentage and improves meat quality. Combined use of MCFA and organic acids increases duodenal villi height and crypt depth in broiler chickens. In addition to blends of single organic acids, blends of essential oils with organic acids have recently been proposed. Testing of such mixtures has shown their effectiveness against pathogen contamination of poultry feed (Satterlee *et al.*, 2023). However, the scheme of feed additives use is of fundamental significance. For instance, the use of a mixture of organic acids and essential oils throughout the production cycle (35 days) with the addition of MCFAs for 5 days immediately before slaughter negatively affected broiler performance (Greene *et al.*, 2022). The authors suggest that this result may be due to changes in the microbiota of the small intestine caused by prolonged exposure to acid. Recent results of a study in Ukraine on the effects of the original SCFAs blend have shown the vital role of adhesion proteins and extracellular matrix in the barrier function of the small intestine (Masiuk *et al.*, 2023). Therewith, mixtures of SCFAs with MCFAs have been shown to be effective in treating poultry infected with Clostridium perfringens, Eimeria spp., and Salmonella typhimurium. At the same time, mixtures of formic acid, propionic acid, and sodium formate, varying in ratio, showed no differences in effectiveness against Salmonella.

CONCLUSIONS

According to the current regulatory framework, specifically EU regulations, the use of antibiotics in poultry farming is critically limited. Currently, OAs are successfully used as a prophylactic alternative to antibiotics. Research has shown that OAs are a cost-effective means of ensuring productivity, antimicrobial protection, and maintaining poultry health. Recent studies have shown that certain OAs improve digestion, immune response, and suppress pathogenic microflora. On the other hand, mixtures of OAs may have more powerful protective and stimulating effects depending on the composition and relative content of each component.

SCFAs have a wide range of effects on metabolism and immune defence in poultry, but despite the available data respectively their effects on metabolism and energy homeostasis, the mechanisms of transport and biological activity is still understudied. Butyrate has been shown to have a positive effect on the intestinal barrier and stimulates the metabolism of enterocytes. SCFAs can modulate the adaptive immune system by stimulating macrophages and dendritic cells. SCFAs are involved in the regulation of gene expression in the cellular response to damage, including infectious agents. Therewith, there is an evidence of the damaging effect of butyrate on the intestinal barrier during inflammation. Considering the above data, the use of SCFAs in poultry production requires a detailed understanding of the protective mechanisms of action on the cells of the intestinal system, as well as the possible risks of inhibiting intestinal function. The total use of SCFAs requires further studies of their effect on the efficiency of the intestinal barrier function and the expression of molecular markers of epithelial cell intercellular adhesion. Along with determining the expression, a significant criterion for assessing the beneficial effect of SCFAs is the production of pro- and anti-inflammatory cytokines by cells of the intestinal system, fatty acid receptors, energy metabolism, and proliferation of intestinal epithelial cells.

Recently, MCFAs have been increasingly considered as an alternative to antibiotics due to their high antibacterial activity, stimulation of absorption, inhibition of lipase production by bacteria and lower dissociation ability compared to other surfactants. However, the mechanisms of MCFAs' action are still unclear. A significant feature of MCFAs is their ability to easily penetrate microbial membranes in undissociated form, which is effective against Gram-positive cocci. The study of the antimicrobial effects of MCFAs mixtures is a crucial component of creating a modern antibiotic-free strategy.

Mixtures of OAs are more effective than their individual use. Mixtures of SCFAs with MCFAs have the most significant beneficial effect since SCFAs act better as growth stimulants and MCFAs have higher antibacterial properties. At the same time, the optimal content of individual OAs in the mixture, doses, and exposure times stays a compromise issue. The use of specific molecular markers to evaluate the effectiveness of OA mixtures will allow the development of criteria for the formation of antimicrobial feed additives with unique properties and a focus that meets the challenges in poultry production. Further research into the mechanisms of action of the OAs will allow the development of their mixtures with optimised properties in terms of antimicrobial protection, intestinal functions, and metabolic stimulation. In addition, OA mixtures can be useful for the prevention of chronic diseases, such as bacterial chondronecrosis and osteomyelitis in broiler chickens.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of financial interest or personal relationship regarding this document.

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Сучасний стан та перспективи застосування органічних кислот та їх композицій в кормах для птиці: Огляд літератури

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Анотація. Застосування антибіотиків в птахівництві є критично обмеженим, що обумовлює пошук і дослідження альтернативних сполук для заміни антибіотиків. Органічні кислоти розглядаються як одна з таких альтернатив, однак антимікробні та метаболічні ефекти сумішей жирних кислот залишаються суперечливими та не повністю зрозумілими. Все це разом обумовлює актуальність системного аналізу сучасних даних стосовно ефективних стратегій заміни антибіотиків. Метою роботи було провести аналіз та узагальнення сучасних уявлень щодо застосування сумішей органічних кислот в якості альтернативної стратегії забезпечення сталого птахівництва. Аналіз сучасних літературних джерел показав, що однією з перспективних альтернатив використанню антибіотиків у птахівництві є суміші органічних кислот та їх похідні, які мають антибактеріальну дію, знижують pH, включаються в енергетичний метаболізм і все це разом сприяє інтестинальній функції. Органічні кислоти позитивно впливають на фізіологічні функції, зокрема, травлення та імунну систему, є основним джерелом енергії колоноцитів та знижують патогенне бактеріальне навантаження на травний тракт. Показано, що суміші органічних кислот виявляють вищу ефективність, ніж їх окреме застосування, зокрема, показана висока ефективність застосування сумішей коротко- та середньоланцюгових жирних кислот для підтримки інтестинального бар'єру, мікробіому та імунітету, при цьому перші краще діють як стимулятори росту, а другі мають вищі антибактеріальні властивості. Ефективність застосування як органічних кислот окремо, так і їх сумішей залежить від багатьох факторів, залежно від типу молекули, форми та дози задавання. Обґрунтовано доцільність проведення подальших досліджень ефектів органічних кислот, що буде корисним для розробки антибіотик-фрі стратегії використовуючи синергічні ефекти їх сумішей та багато спрямовану цитопротекторну дію. Робота стане в нагоді науковцям та ветеринарним лікарям для ознайомлення з перспективами застосування композиції органічних кислот як замінників антибіотиків, зокрема для формування технологічних прийомів з мінімізацією їх використання

Ключові слова: суміші коротколанцюгових та середньоланцюгових жирних кислот; птахівництво; антибіотики; підтримка інтестинальної функції

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